EUROFUSION WPJET1-PR(16) 15332

C Klepper et al.

Extending Helium Partial Pressure Measurement Technology to JET DTE2 and ITER

Preprint of Paper to be submitted for publication in
21st Topical Conference on High Temperature Plasma Diagnostics 2016

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Extending Helium Partial Pressure Measurement Technology to JET DTE2 and ITER[a)]

C.C. Klepper[1], T.M. Biewer[1], U. Kruezi[2], S. Vartanian[3], D. Douai[3], D.L. Hillis[1], C. Marcus[1], and JET contributors[b)]

EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK
[1]Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6169, USA
[2]CCFE, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK
[3]IRFM, CEA Cadarache, 13108 St-Paul-lez-Durance cedex, France

(Presented XXXXX; received XXXXX; accepted XXXXX; published online XXXXX)

The detection limit for helium (He) partial pressure monitoring via the Penning discharge optical emission diagnostic, mainly used for tokamak divertor effluent gas analysis, is shown here to be possible for He concentrations down to 0.1% in predominantly deuterium effluents. This result from a dedicated laboratory study means that the technique can now be extended to intrinsically (non-injected) He produced as fusion reaction ash in deuterium-tritium experiments. The paper also examines threshold ionization mass spectroscopy as a potential backup to the optical technique, but finds that further development is needed to attain with plasma pulse-relevant response times. Both these studies are presented in the context of continuing development of plasma pulse-resolving, residual gas analysis for the upcoming JET deuterium-tritium campaign (DTE-2) and for ITER.

I. INTRODUCTION

A. Diagnostic Residual Gas Analyzers

Residual gas analysis for the next generation fusion energy device, the ITER tokamak, will include measurements during the plasma pulse. The systems that have this function are referred to as Diagnostic RGAs (DRGA). The ITER divertor DRGA, described in more detail in Ref [Klepper-2015] is designed for ~1s response time, despite a ~8m separation of the sampling region to a differentially-pumped *analysis chamber*, which hosts all the pressure and partial pressure sensors. The sensors, key to the analysis of the composition of the divertor effluent neutral gas, include mass spectrometers as well as an optical gas analyzer, using a Penning ionization gauge as the excitation source for the plasma light emission to be analyzed. This technology, also referred as Penning optical gas analyzer (OGA), was already demonstrated on several current generation tokamak, including the JET tokamak, in which it was applied not only to the separation of ^{4}He from D_2 (these species not being separable by standard mass spectrometers due to their nearly identical masses, i.e. amu ~4) but also for resolving $H_2/D_2/T_2$ through high-resolution spectroscopy of the Penning-OGA emitted Balmer-alpha line. This last application most valuably deployed in the last deuterium-tritium experimental campaign (DTE1) of JET [Hillis-1999] and this also served as a "real-life" qualification of the diagnostic technique for use on ITER, including its DT phase. In fact, the Penning OGA technique constitutes the only DRGA sensor technology (i.e. differentially pumped and plasma pulse-resolving) to have been demonstrated in a DT environment.

In parallel and synergistically with the ITER DRGA development is the continuing development of a full DRGA system for the next D-T operation on JET (DTE2, presently envisioned for ca. 2020). In addition to Penning OGA sensors, the JET DRGA will include plasma pulse-resolving mass spectrometers. This means adding the existing and new mass spectrometer sensors to the same, tritium plant-compatible, differential pumping environment as the OGA. It also means continuing to improve on both fringing magnetic shielding and time-resolved data acquisition and controlled. There have been important aspects of continuing evolution of this pulse-resolving mass spectroscopy-based, residual gas analysis over the last 2-3 decades (see, e.g. [Klepper-2010]).

B. The Penning-OGA detectability limit question

While the isotopic ratios measurement application of the Penning-OGA to JET-DTE1 was shown to detect concentrations down to the 1% level, in good agreement with the concentrations measured on the main plasma side with both divertor plasma optical spectroscopy and energy-resolve neutron analysis, the detectability limit for the He concentration measurement remained hereto unknown. The later measurement was successfully applied to He transport, as well as to desorption of hydrogen isotopes from the walls studies [Hillis-2003] but these applications involved external injection of He into the tokamak, at concentration levels up to 100%. However, the application of this measurement technique to DT-produced He, as fusion

[a)]Contributed paper published as part of the Proceedings of the 21st Topical Conference on High-Temperature Plasma Diagnostics (HTPD 2016) in Madison, Wisconsin, USA.
[b)] See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia.

reaction ash, would require detectability down to fractions of 1%. For early JET DT operation, ~0.5% He concentration is predicted [Klepper-2015].

A first, systematic study of the He detectability study, carried out for conditions similar to the application of this measurement as part of the ITER DRGA, is discussed in Section II.

Section III of this paper examines the examines the use of threshold ionization mass spectroscopy (TIMS) as a potential backup to the optical technique for important measurement and shows that there is some further development needed to make this approach compatible for measurement during the plasma pulse.

C. The question of TIMS as a He concentration back-up measurement

The mentioned importance of the He concentration measurement for DT plasma, especially for intrinsic (DT reaction-produced) He, also generates interest in a back-up measurements, especially in the ITER DT environment, where there are DT-specific risks to the OGA, including radiation-induced light attenuation, as well as luminescence, in the optical fibers.

The TIMS technique has been well described in [4 - 6]. It involves taking advantage of the difference in ionization thresholds between the 2 mass-4 species of interest. Although earlier studies, aimed specifically for JET, showed promising species separation, an ability to carry out this measurement in plasma pulse-resolving time scales has not been demonstrated.

II. HELIUM DETECTABILITY VIA PENNING-OGA

Except for the isotopic ratio measurement, were high-resolution, optical spectroscopy has been applied, most Penning-OGA applications rely on filtered photodetectors. One of the known effects that impact the ability of the Penning-OGA approach to detect small concentrations of any impurity in a hydrogen isotope background is the impact of continuum emission, within the band-pass of the impurity line filter, including that from hydrogen molecular bands and quasi-continua. This has been, e.g., documented for neon (Ne) in Ref [Klepper-1997]. In the case of DT plasmas, radiation induced luminescence can also add to this effect. Mainly for this reason, the emerging approach to this measurement includes the use of spectrally-resolving detection even for spectrally isolated lines.

For the He detectability study, the same McPherson 2051 spectrometer used in [Klepper-1997] but now equipped with a PhotoMax camera, was deployed with a coarse (300 G/mm) grating, such as to fit both the D_α 656.1nm line and the He I 667.8 nm line simultaneously on the 500 pixel-wide CCD chip. The study was carried out on the ITER DRGA prototype test-stand located at ORNL.

To assure proper mixing of the injected gases, particularly with one species at fractions of 1% concentrations, a dual-reservoir, gas mixing and delivery system was developed (Fig. 1). The gases are successively introduced into the first reservoir, while monitoring the total pressure with a high-pressure capacitance manometer, to obtain the desired composition.

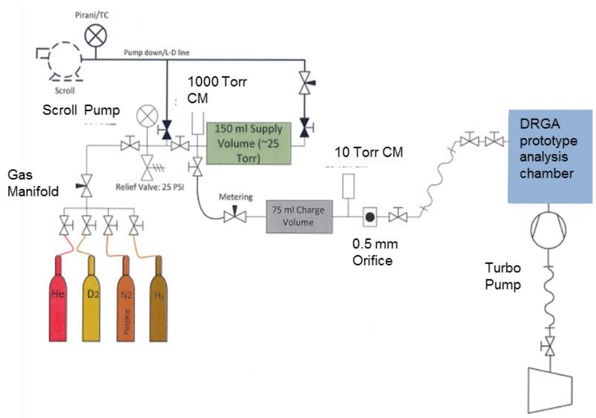

Figure 1. Gas mixing and delivery systems for testing with small (<1%) minority species concentrations. Between experiments, both reservoirs are pumped down with the scroll pump.

This second reservoir is loaded to a total *charge pressure* of up to ~20 mbar. Furthermore, an additional equilibration time of several minutes is still allowed, at each experiment, before introducing the mixed gas into the second reservoir, to a supply pressure of ~0.2 mbar. This pressure is chosen specifically to introduce the mixed gas, through an orifice (into the prototype analysis chamber) with roughly the same throughput as the design gas throughput for the ITER Divertor DRGA [Klepper-2015].

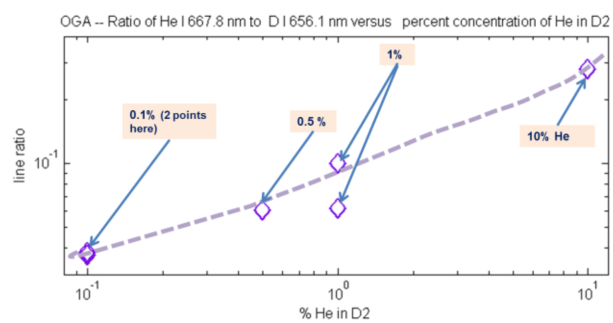

Figure 2. Neutral helium to deuterium spectral line ratio as a function of He concentration in the injected He/D_2 gas mix.

Figure 2 shows the line ratio versus concentration for this first systematic study down to 0.1% He concentration. The dashed line is provided to guide the eye. Points near this line were all recorded at the same neutral pressure in the OGA sub-chamber ($4x10^{-5}$ mbar). The lower of the two points at the 1% concentration was recorded when the pressure had dropped in that region to $3x10^{-5}$ mbar. It is recalled that in the case of the ITER DRGA, the OGA is placed at the inter-stage port of the turbo-molecular pump so as to provide a higher pressure (for more light emission) that in the main analysis chamber, which was in the mid-10^{-6} mbar scale for the present study.

It is clear that the line ratio continues to be sensitive to concentration well below to the 0.5% concentration expected for intrinsic He in the early ITER DT phase. The data also recall that this is an indirect measurement of the partial pressures and that the calibration must always take into account any changes in the total pressure in the Penning discharge.

It is noted however that these measurements were made with CCD camera exposure times of 10, 50, 100, 90, 90 s for the experimental points acquired sequentially with 10, 1, 0.1, 0.1, 0.5 % He concentration correspondingly.

III. TIMS VIABILITY AS A HELIUM EXHAUST BACKUP MEASUREMENT

The TIMS technique is being revisited in the framework of the JET DRGA upgrade and with specific focus on the ability to apply it with plasma pulse-relevant response times. As mentioned, existing data originates from studies on vacuum tests-stands and with long integration times. In general, the approach is purported to involve measurement of the ion current for the same mass (mass 4 for $^4He/D_2$ differentiation, mass 3 for $^3He/HD$, mass 20 for CD_4/D_2O and so on) but at 2 different ionized (electron) energy, one just below and one above the ionization threshold of the higher ionization energy species (e.g. ^4He in the case of $^4He/D_2$).

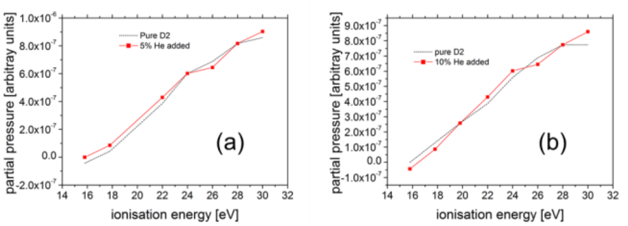

Figure 3. No-plasma, calibration pulses in JET with the Hiden Analytics mass spectrometer set to operate at only mass 4, but at multiple ionizer energy steps (8 steps, each followed by ~100ms multi-amu read-out). Data shown for (a) 5% He in D_2, (b) 10% He in D_2.

Recent studies with gas injection (without plasma) in JET, but with pulse-relevant acquisition times and relatively small (5-10%) helium-to-deuterium injected, have examined this with several energy points acquired (Fig. 3). These studies show that even with several points it is difficult to differentiate the data with small helium content. It suggests the either more points are needed or a good computational model to fit that points. A balanced would need to be reached between number of points acquired and the desired time resolution for the measurement.

IV. CONCLUSIONS AND DISCUSSION

The Penning-OGA technique, owing to its successful deployment in JET DTE1's radiating and tritium environment, is presently part of the suite of partial pressure sensors for diagnostic RGA systems for both JET DTE2 and ITER. In the present work, it has been shown that the He concentration measurement can, in fact, be extended to small (sub-1%) concentrations, such as for DT-produced He ash.

The non-optimized spectrometer and light-collection did not permit to demonstrate measurement of these low concentrations with response times compatible with the vacuum conductance limit of 1-2 s for the DRGA systems under design. However, more recent measurements on the TCV tokamak (by the CEA co-authors) have used an optimized spectrometer system and have shown promising measurements the He line clearly detectable to He partial pressures down to <~ $4e^{-5}$ Pa (~$0.01*4*10^{-5}$ mbar, thus comparable to our 1% He/D_2 data point) with <~ 1s response time [Douai, Vartanian-2016]

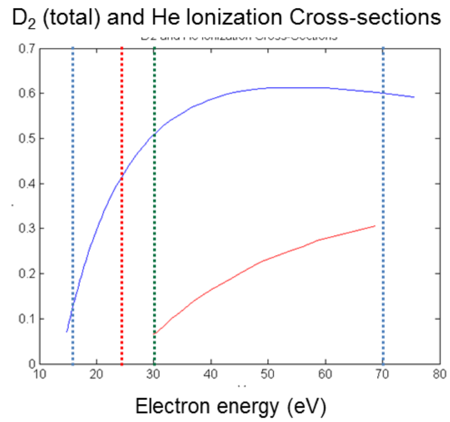

Figure 4. Theoretical Ionization curves for D_2 (blue curve) and He (red curve). Vertical lines mark energies chosen in published studies.

As mentioned, the stated approach for TIMS (for mass 2) is to measure the same mass at a point before the He ionization threshold and one right after ([4,5], e.g.). A newer study uses 25, 70 eV [6]. None of these earlier studies is done in times compatible with the desired time resolution for JET or ITER DT. The difficulty with extracting [He]/[D2] with just 2 points, can be clearly see when plotting ionization curves for both species on the same graph. For instance, between 25 and 30 eV, $\sigma(He) << \sigma(D_2)$. In pure D_2, (0% He) the intensity at m/z=4 is $I4= [D_2] * \sigma(D_2)$. With 5-10% He, the mass 4 ion current will be $I_4= [D_2] * \sigma(D_2) + [^4He] * \sigma(^4He) \sim= [D_2] * \sigma(D_2)$, i.e. very difficult to detect this effect.

Upcoming testing on JET will work with more energy points than in Fig. 3, aiming to develop a clearer, empirical model for the difference in the slopes (and how it relates to %He) while trying to keep near the desired response time (~1 – 2 s).

XII. ACKNOWLEDGMENTS

Work supported, in part, by the US DOE under Contract No. DE-AC05-00OR22725 with UT-Battelle, LLC. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

XIII. REFERENCES AND FOOTNOTES

1[Klepper-2015] C.C. Klepper et al., Fusion Eng Des **96–97** , 803 (2015)

2[Klepper-1997] C. C. Klepper, D. L. Hillis, M. R. Wade, R. Maingi and G. R. McKee, Rev. Sci. Instrum. **68** Issue 1 (1997)

3[Hillis-1999] D. L. Hillis, P. D. Morgan, J. K. Ehrenberg, M. Groth, V. Kumar, M. F. Stamp, and M. von Hellerman, Rev. Sci. Instrum. 70 Issue 1 (1999) 359

4[Coyne-2009] S. Davies, T. Coyne, C. Robertson, N. Balshaw, D. Brennan, A. Miller, C. Whitehead, JET-EFDA Contributors, "Deconvolution of complex residual gas spectra at JET," IEEE/NPSS 36th international conference on plasma science and 23rd symposium on fusion engineering conference, ICOPS-SOFE 2009, San Diego, USA, (31st May 2009 - 5th June 2009).

5[Davies-2014] S. Davies, J.A. Rees, D.L. Seymour, Vacuum **101** (2014) 416

6[Yu-2015] Yaowei Yu, Jiansheng Hu, Zhao Wan, Jinhua Wu, Houyin Wang, and Bin Cao, Rev. Sci. Instrum. 87, 019501 (2016)

7[Klepper-2010] [3] C. C. Klepper, D. L. Hillis, J. Bucalossi, D. Douai, P. Oddon, and S. Vartanian, Rev. Sci. Instrum. **81** (2010) 10E104

8[Hillis-2003] Hillis, et al., Rev. Sci. Instrum., Vol. 70, No. 1, January 1999

9[Douai, Vartanian-2016] D. Douai et al., "Development of Helium Electron Cyclotron Wall Conditioning on TCV for the operation of JT-60SA," to be published as synopsis in Proceedings of the 26th IAEA Fusion Energy Conference, Kyoto, Japan, 17th - 22nd October 2016