SUBDIVERTOR FUEL ISOTOPIC CONTENT DETECTION LIMIT FOR JET AND IMPACT ON THE CONTROL OF ICRH FOR JET-ILW AND JET-DT OPERATION\(^1\)

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Abstract

The ability to detect and control fuel isotopic content down to a 1% concentration level is greatly important for the upcoming JET DTE2 campaign, as well as its associated TT and DD phases. A reduction of H minority concentration even from 2% down to 1% is shown here to have significant impact on the effectiveness of ICRF core heating, while the ability to maintain T or D concentration at or below 1% is critical to limiting fusion neutron generation in the DD and TT phases, correspondingly. The subdivertor measurement of (global) isotopic concentration, based on Penning-activated optical spectroscopy can deliver minimally this 1% detection for DTE2 as long as light collection from the Penning emission can be optimized and gradual window transmission deterioration can be minimized. This is simulated with a statistical analysis developed to understand the uncertainty sources in the JET DTE1 data, as well as to guide the optimization of an upgraded, fuel-isotopic content (and helium-ash concentration) gas analysis system for the JET divertor in preparation for DTE2. While this random error can be reduced to allow measurement substantially below 1% concentration, analysis also shows a systematic error of up to 1% understood to be due to plasma-surface interactions in the Penning excitation, suggesting that 1% may still be the low-end limit for the subdivertor measurement, unless a Penning-source conditioning approach is also developed.

1. INTRODUCTION

The upcoming JET deuterium-tritium (D-T) campaign known as DTE2 (D-T Experiment 2) will constitute the second such nuclear phase of JET, with DTE-1 having occurred nearly 2 decades earlier [1, 2]. Unlike DTE-1, which took place in a carbon wall environment, DTE-2 will take place in the present ITER-Like Wall environment. On the other hand, the change to a more reactor-compatible wall material has also also required upgrade of key diagnostics, such as Charge-Exchange Spectroscopy, whose upgrade improves core plasma ion temperature measurement in absence of significant C impurity content in the plasma [3]. Along these lines, and to assure readiness to provide measurement important to fusion fuel cycle for DTE2, a study was performed to determine the detection limit for fuel isotopes in the subdivertor region. It focused particularly in the measurement provided

\(^1\) This manuscript has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

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by Penning optical spectroscopy, also known as optical gas analysis (OGA). In the present study, the DTE-1 OGA data [4] were revisited with focus on the uncertainty of the measurement on the low concentration end.

In parallel with this, the significance of getting measurement resolution down to the 1% level (or below) to a successful DTE2, as well as to the TT phase of the upcoming JET campaign, which will precede DTE2 and the DD campaign with will follow, has also been explored. In this part of the study, the impact changes in isotopic minority concentration around the 1% concentration level on the effectiveness of ion cyclotron resonance heating on increasing the ion energy content is examined, based on pulses from earlier JET campaigns.

DTE2 will be carried out in the present ITER-Like Wall environment of JET. Both the feasibility of the fuel isotopic measurement down to these low levels, but also the significance of achieving these particularly low detection minima on DT plasma performance, are both of great importance to the design of measurement capability for ITER, in particular for its nuclear phase, where the measurement is most challenging.

In the present paper, Section 2a is devoted to the reexamination of isotopic ratio from past campaigns, including the tritium concentration data from DTE1 and a large set of more recent data from ICRH discharges, with main focus on the error bars and their trend at or near the ~1%-concentration level. In Section 2b, JET-ILW pulses with H-minority ICRF heating and with H concentrations at and below 2% are examined with focus on the impact on electron/ion heating and W core concentration. In Section 3, the significance DTE2-related neutron budgets of fuel isotopic content measurement and control down to this low level is briefly discussed. In Section 4, the focus returns to the measurement of the isotopic ratio, this time with focus on improvements in the measurement approach in preparation for DTE2. This Section also includes use of a newly developed simulation tool, which can simulate the spectral profile of the Balmer-alpha spectral lines, with two or more isotopic components, including the propagation of error to estimate the uncertainty of the measurement. The tool is intended to guide the optimization of the measurement for DTE2. In Section 5, to connection between subdivertor and main plasma isotopic composition is discussed and an overall summary is provided in Section 7.

2. ISOTOPIC DETECTION LIMIT DURING AND SINCE JET DTE1

2.1. Tritium concentration measurements in DTE1 and associated low end detection uncertainty

In the present study, the DTE-1 OGA data [1] were revisited with focus on the uncertainty of the measurement on the low concentration end. The data plotted in Fig. 1 are the same OGA data plotted, e.g., in Fig. 5 of Ref [1], however with the error bars now added and displayed with the data. The latter are from the error analysis carried out as part of the original fitting of the spectral profiles, which produced the isotopic concentration data for [1] and has since continued to automatically process data for this diagnostic.

It can be seen in the present Figure that as the 1% T/(H+D+T) tritium concentration level is approached, the uncertainty in the measured concentration approaches 100% of the measurement value (Fig. 1). This suggests a 1% lower limit to the isotopic content measurement with this technique.
Insight to the causes of the substantial relative uncertainty in the low concentration data can be most simply gained by observation of an actual, optical spectrum from this set of data. Figure 1b shows Penning-excited optical spectrum from the DTE1 published set, in this case for ~11% T and ~1.5% H concentrations, to illustrate the challenge of extracting the low concentration of these isotopes in a deuterium background. Firstly, it is noted that the overall intensity level (in number of CCD detector counts) is quite small. The D-alpha peak minus the continuum is barely above 100 counts. The saturation limit of the CCD detector was 32,000 counts. Thus, the full dynamic range was far from being utilized. It has been found relatively recently that the inherent property of Penning (and the related Magnetron-) type discharges to produce thin film coatings greatly contributed to the paucity of Penning plasma-emitted light, which is in itself a relatively low emission source, by depositing carbon-based coatings onto the viewport windows. That, in turn, reduced light transmission and therefore the amount of light that can be collected for spectroscopic analysis.

This reduced light level then affects the detection limit of the tritium detection in a more complex way that the hydrogen detection. With state-of-the-art, passive optical spectroscopy used for DTE1, one can see in Fig. 1b that the H minority species is spectrally well separated. As such, it seems to be affected primarily by the relatively low spectral line signal over the random noise. On the other hand, the close spacing of the D and T components means that the low S/N also compounds the error of the non-linear fitting, which is necessary to distinguish the T from the D component (as also seen in Fig. 1b).

It is noteworthy, however, that this detection limit, as derived by simply reexamining the existing, analyzed JET DTE1 data, matches impressively well the detection limit derived from a more recent, laboratory-based study, using H as a proxy for T in H/D mixtures, for an equivalent sub-divertor gas analysis system designed for ITER [5]. The system includes the same type of plasma excitation source, however with a different differential pumping arrangement with respect to the main analysis region. The fact that the laboratory study allowed for large integration times to overcome low S/N would suggest that additional mechanisms may be preventing H detection below the 1% level.

It is finally noted that mentioned, historically used, automatic fitting program basically fits the spectral profile of each isotope Balmer-a line (i.e. Ha-6562.79 Å, Da-6561.03 Å, and Ta-6560.44 Å) to an empirical model of 2-co-centric Gaussian profiles [6]. Although the model has been interpreted as corresponding to the emission from both (“cold”) atomic species and from (“hot”) molecular dissociation species, no actual atomic or molecular physics is involved in the fitting of the lines. An ongoing effort, in parallel to the present study, is attempting to further improve spectral fitting by introducing atomic and molecular physics into the fitting program [7].

2.1. Hydrogen concentration measurements after DTE1 and ahead of DTE2 capability upgrade.

The present study also examined measurement uncertainty in a large set of data from more recent experimental campaigns, particularly focusing on comparison of the OGA data to those from divertor spectroscopy, i.e. measurement directly in the divertor plasma (with the local plasma also providing in this case the excitation source for the emission). This dataset was taken from a database specific to ICRH physics studies. Figure 2 shows this data comparison for the set, together with the error bars. Similarly, the latter come from the standard JET automatic fitting program, which computes the isotopic ratios from the spectral profiles.

Figure 2. Isotopic concentration from divertor spectroscopy plotted versus the subdivertor Penning optical gas measurements: (a) Full range examined in log-log scale; (b) data only up to 4% concentration, based Penning spectroscopy values, to more clearly show the offset in values at low concentrations. The dashed line is an approximate linear fit to the data and the solid lines are there to highlight the shift of the OGA values wrt the divertor spectroscopy.
Much like in the case of the DTE1 T concentration, the error bar in the H/(H+D) concentration can be seen to exhibit a ~1%-concentration uncertainty in the measurement as the 1% concentration level is approached. Furthermore, a systematic error of also about 1% is manifested, in the form of a positive offset of the OGA measurement about the divertor spectroscopy values. Therefore, the detailed evaluation of this set of data further reinforces the idea that, at least the hydrogen as a minority isotope, manifests a detection limit determined by two separate effects: Signal to noise (S/N) limitations due to low light transmission/collection of the Penning source-emitted light and the observed, systematic offset. As a caveat, it is also noted that the divertor spectroscopy is sensitive to the strike point position which could also be contributing to the spread in the data shown in Fig. 2.

It is important to note that the systematic error does not scale up at large isotopic concentrations and, as such, it is not considered to be a result of isotopic differences in gas dynamics between divertor and subdivertor regions. Instead, it is presently considered to arise largely from intrinsic H sources inside the OGA’s own plasma source, a topic of an ongoing laboratory study [8]). On the other hand, the random error is manifestly due to limitations in light emission from the OGA source and light losses from source to detection and can only be reduced by improved light emission or collection and by the mitigation of light transmission losses. As will be discussed later in the paper, an upgraded, multi-sensor (including shielded mass spectrometers) gas analysis diagnostic for DTE-2 is aiming to reduce light losses for the OGA part of the system, partly by mitigation of window coatings produced by the Penning plasma source. Divertor species-concentration analysis – and especially the OGA part - remain a critical fuel isotope diagnostic as JET DTE2 is approached. It is also likely the main way to diagnose and control the isotopic concentration in ITER, especially at these low concentration levels. This is due to the increased challenge of fitting main divertor spectra, in the presence of significantly more spectral broadening, as well as more complex reflected light issues in ITER’s metal wall environment (see, e.g. discussion and references provided in [5]).

3. IMPACT ON CORE PLASMA HEATING WITH ICRH

The importance of resolving isotopic concentrations at the ~1% level during plasmas with ICRH can be seen in Fig. 3. When the hydrogen concentration is reduced from 2.5% to below 1% (here based on divertor spectroscopy) in high NBI power H-mode discharges, 2nd harmonic Deuterium ICRF power absorption becomes dominant over the fundamental Hydrogen minority one [9, 10]. In such conditions, Deuterium ions (both from the thermal background and in particular from the injected NBI subpopulation) are accelerated to high energies, as seen by the neutral particle analyser (NPA) measurements for Deuterium at E=300keV. These fast D+ ions not only lead to a considerable enhancement of the neutron yield with respect to the standard H minority case with similar Ti (not shown) but, in combination with the fast H+ ions (that are also accelerated to significant energies due to their small fraction) cause full stabilization of the sawtooth activity during the high ICRH power phase in the given example (JET Pulse 89192). Note that the total radiation is similar in the two cases showing that equivalent high-Z impurity screening is achieved in both discharges.

![Figure 3. Two similar discharges with H/D<~1% (red lines) and H/D=~2.5% (blue lines) from divertor spectroscopy (larger for optical Penning spectroscopy). JET Pulses 89192 -93, correspondingly.](image-url)
Another example of the sensitivity of ICRH heating to the H concentration is given in Fig. 4, where data from a series of similar H-mode discharges in JET-ILW with varying H injection are shown. When the $H/(H+^3He)$ ratio is scanned from 23% to 2%, the central electron temperature (left) increases continuously confirming that electron heating (after collisional redistribution) is maximized for low H minority concentrations (~2%). Since electron heating with ICRH has proven beneficial for high-Z impurity control in JET-ILW [10, 11], the core tungsten (W) content (as measured by soft X-ray) is also reduced at the lowest hydrogen levels.

The above examples would imply that the ability to measure, and ultimately control, the fuel isotopic content down to the 1% concentration level is important for optimizing the performance of a given ICRH scheme in fusion devices. This is particularly important when using $^3$He minority heating or for inverted ICRH heating scenarios, where a small overshoot of the minority concentration can have a strong impact on the wave absorptivity and on the fate of the RF power absorbed in the plasma [12]. Similarly, the so-called H-$^3$He-D 3-ion scheme needs fine control of the minority $^3$He ions’ concentration at very low levels (<1%) to be efficient [13]. Parenthetically, this case is also of interest regarding the upgraded divertor gas analysis diagnostic, as it can now provide the potential for He detection down to a 0.5% level [14].

4. IMPACT ON NEUTRON BUDGET FOR PRE- AND POST-DTE2 OPERATION

The ability to have an isotopic content detection limit at or even below the 1%-cone level is also of great importance to the envisioned pre-DTE2 (TT) and post-DTE2 (DD) campaigns, in limiting the D/(D+T) content for the former, the T/(D+T) in the latter, thus effectively minimizing fusion neutron production for these phases [15]. JET has contractual limits on the vessel activation due to the total 14 MeV neutron fluence over the lifetime of JET (2x10$^{21}$ 14 MeV neutrons, of which 0.3x10$^{21}$ have been used in DTE1). The 14 MeV neutron production is measured for each pulse and the vessel activation is computed for the vessels composition. The in-vessel activation levels are measured during shutdowns. Thus, each campaign at JET has a 14 MeV budget, staying inside the total 14-MeV limit for the lifetime of JET. In this scheme, pre-campaign estimates are based on having (worst case) 1% D/(D+T) for TT campaigns, providing an estimate for the number of high power pulses that can be done during the campaign. For DT campaigns, the pre-campaign estimates use 50:50 DT concentrations for neutron estimates. Thus, the significance of the low end, fuel isotope detectability is most relevant in the TT and DD campaigns and, in fact, this is an area here a lower detection limit than 1% could be of value.

5. OPTIMIZATION OF FUEL ISOTOPE DETECTION FOR DTE2

An upgraded, multi-sensor, diagnostic system has been recently completed to provide for JET DTE-2 a more complete, plasma pulse-relevant, divertor gas analysis capability than was available for DTE1 (some discussion in [14]). In fact, for the latter, only the OGA measurement was able to provide gas species concentration information during the pulse (mass spectrometers were available but only post-pulse gas analysis). A key feature
of the present upgrade is a scheme to reduce light losses for its OGA measurement, partly by mitigation of window coatings produced by the Penning plasma source (Fig. 5).

Figure 5. Illustrating the pulse-relevant, divertor gas analysis capability upgrade, with emphasis on improved collection of light from the Penning excitation source, as well as mitigation of gradual loss of window transmission due to coating deposition. (Shapes of optical and vacuum components are purely schematic figure and do not represent detailed design). In addition to improvement to the Penning-based optical gas analysis (OGA) measurement, the upgrade also brings in pulse-resolving mass spectroscopy capability, which was not available in DTE1, but is outside the scope of the present paper.

The spectroscopic detection system is also being currently upgraded with aim to improve D/T resolution and the overall dynamic range. In support of this hardware effort, an evolving, advanced spectral fitting program at CEA-IRFM, featuring full error statistics capability, has been run for the present study in simulation mode. The aim is to evaluate what aspects of a hardware system configuration would most improve isotopic detection (especially at super-low concentrations) with particular focus on resolving T from D, as this is more dependent on fitting the spectral profiles than detecting the hydrogen.

Figure 6 shows a simulation for conditions relevant to the DTE1 data showed earlier (Fig. 1). The simulation first produces a theoretical D-alpha/T-alpha profile, for a given concentration and with each isotopic component comprising two Gaussians (“cold” and a “hot” components) according to [6]. Random noise is then added (here the noise level typical of the DTE1 data is used). Subsequently, a large number (~10,000 in this example) non-linear fits are carried out (with the noise generated at random). The statistics then provide the upper and lower, +/- 95% confidence interval, in the resulting fitting results (Fig. 7a). That means that, for an input tritium concentration $[T]_0$, and for given signal intensity and noise level, the measurement will be in the range $[T]_0 \times (1 - \epsilon_{lower}), [T]_0 \times (1 + \epsilon_{upper})$, where $\epsilon_{lower}$ and $\epsilon_{upper}$ are plotted in Fig. 6(a).

Figure 6. Simulation of DTE1 fuel isotope ratio spectra, with statistical analysis of error. Cases for 3 peak intensities, each with +/- 12cts of random noise (similar to DTE1 data) and 0.118Ångstroms/pixel linear dispersion (in all cases the intrinsic instrument function for the spectrometer is taken as 0.3Å FWHM for a 50micron slit). (a) Log-log plots of $\epsilon_{upper}$ and $\epsilon_{lower}$ versus T content with the vertical lines (in corresponding color) showing where uncertainty in the determined concentration value reaches 100% of the value. (b) Fit of simulated profile for 19% T content, also showing “cold” and “hot” components from the fit to compare to the ones of the simulated spectra.
In this case, the simulation was carried out for 3 levels peak intensity. At the same random noise level this gives 3-levels of S/N; this can be also thought of as three level of use of the full dynamic range of the detector system. A simulated profile for 19% T concentration is shown in Fig. 7b for a poor S/N case, much as was the case of the DTE1 data, for comparison with Fig. 1b. The S/N has clearly great impact on the detection limit. In fact, other cases ran with this simulation examined sensitivity to other instrument features, such as the spacing of the detector pixels. But these were not as important as the S/N. Looking, for instance, back at Fig. 6a, for the condition that give only ~200 counts peak intensity, the error in T detection is already reaching 100% of the concentration value at 7%-conc. With medium signal level of about 2000 cts, one get down to 0.7% concentration before the uncertainty reaches 100% of the value. This supports the strong emphasis put on ways to optimize light transmission/collection, as well mitigate the progressive deterioration thereof, due to coating of the windows by the Penning discharge, as discussed earlier in this section.

6. RELATION BETWEEN SUBDIVERTOR AND MAIN PLASMA ISOTOPIC CONTENT

It is important to mention that any isotope concentration measurement done outside the plasma does not necessarily reflect the absolute concentration of that isotope in the plasma core and transport modelling including additional particle sources (e.g. NBI or fusion alphas) should, in principle, be pursued to establish a proper link between these quantities, for the specific plasma conditions of interest. However, there is also significant experimental evidence to convince that, for plasma-wall equilibration timescales, the hydrogenic isotopic content in the sub-divertor matches that of the main plasma. This is likely because, in such timescales, there is enough exchange of particles between main plasma and (neutralized) subdivertor gas that the analysis of the latter serves as a global measurement of isotopic content of the former. Two highly relevant examples of this for present generation tokamaks are (a) the JET DTE1 data of Ref [1] in which great agreement is shown between subdivertor and main plasma measurements (including neutrons) over a very large range of isotopic concentrations and (b) a long-pulse, particle balance study on Tore Supra in which it was specifically shown that the subdivertor optical Penning measurement was in full agreement with neutral particle analyzer (NPA) data from the core, thus permitting the former to continue taking data over much longer time scales than was possible for the latter diagnostic [16]. This should however be check (via modeling) for ITER, especially since it has already been established that isotopic measurement by divertor spectroscopy will not be feasible at low concentrations.

7. SUMMARY AND CONCLUSION

Reexamination of isotopic content data, from automatic fitting of optical spectra of the Penning-OGA system on JET, both from DTE1 pulses (with focus on T content) and from more recent ICRH physics pulses (with focus on H minority content) shows that resolving isotopic content at the 1% or lower level can be challenging and requires special attention. In particular, preventing the loss of light through window transmission losses, can greatly impact the ability to maintain detectability at this level and prevent progressive loss of this capability. The current system upgrade includes a way to mitigate light loss resulting from thin film deposition on the viewing port of the OGA.

The importance of maintaining detection capability down to this small concentration level for the JET DTE2 campaign has also been examined. Specifically, it is seen that for maximizing ICRH core heating in DTE2, the impact of lowering H content from 2% to 1% can have substantial impact. It has also been noted that the TT and DD campaigns, ahead and after DTE2 respectively, the same reduction in the T content can have substantial impact on the neutron budget. Loss of light from the Penning plasma source doubly impacts T detectability: (a) direct impact by reducing S/N and (b) indirect impact by forcing diagnostic operators to trade instrumental function width for more light into the spectrometer, making it harder to resolve T/D components of the Balmer-alpha line.

Not included in this paper is a discussion of the effect of plasma-surface interactions inside the Penning discharge tube, where neutrals are ionized and plasma light emission is produced in the process, and then used to determine the concentrations of the emitting species. This interaction, in particular in the form of hydrogen desorption from Penning electrode stainless steel surfaces (as well as isotopic exchange effects) is suspected to play a role in the detected systematic shift of the OGA-based H-content data and is a topic of current laboratory studies [VARTA-2018]. Even including this effect, it is clear that, for DTE2, presently upgraded, subdivertor gas
analysis capability is expected to provide measurement minimally down to the 1% level in support of JET DTE2 campaign needs.

ACKNOWLEDGEMENTS

Valuable discussions on the impact of isotopic concentration on neutron budgets are gratefully acknowledged. This work was supported, in part, by the US DOE under Contract No. DE-AC05-00OR22725 with UT-Battelle, LLC. 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.

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