68th Annual Technical Conference Proceedings
Nashville, TN, USA May 19 – 22, 2025
https://doi.org/10.14332/svc25.proc.0000

ISSN 0737-5921
ISBN 978-1-878068-45-3

Understanding the Quadrupole Mass Filter and Testing a High-Resolution QMS RGA for ITER

C. Marcus[1], R. Mellor[2]
[1]Oak Ridge National Laboratory, Oak Ridge, TN, 37831 USA
[2]Hiden Analytical, 420 Europa Boulevard, Warrington, WA5 7UN, UK

ABSTRACT

A common type of residual gas analyzer is the quadrupole mass spectrometer. One of the main components within this instrument is a mass filter known as the quadrupole. It is responsible for the selective throughput of the ionized gas particles - by ascending mass number - prior to ion impacts on the analyzer (or detector) surface from which the ion current signal is generated for processing. However, the quadrupole is not fully described in relation to the electric field characteristics and the function as an ion mass separator. This paper describes the basic origins of the electrical design, the intricate assembly criteria, and performance of the quadrupole within the spectrometer.

A specialized quadrupole mass spectrometer is part of a configuration for a diagnostic gas analyzer system planned for ITER, a fusion research machine. It has a verified capability, essential as a diagnostic criterion for this reactor project, to successfully deconvolute the mass signals of Helium-4 and deuterium (reactor fuel exhaust gases, separated by only 0.026 atomic mass units), down to a relative three-percent concentration of the former gas. The associated preliminary testing, performed at the Oak Ridge National Laboratory, is also addressed. Finally, one of the key parameters used to express gas concentration, the relative sensitivity factor, will be explained, including an evaluation of dependency on other variables.

INTRODUCTION

The quadrupole mass filter has been well described in published literature and highly reputed within the mass spectroscopy user forum for effectively resolving ion mass species. This component is part of the quadrupole mass spectrometer (QMS). In the context of this paper, it is associated with the residual gas analyzer (RGA). Typically, the corresponding scan bandwidth of these species is 1-100 atomic mass units (amu).

From the general user standpoint, the electrical and physical details, which enable this ion mass filtering function, are not fully understood. It is important to describe this component, in a broad sense, as a precursor to presenting data herein, acquired using a unique, specialized QMS: The HAL 101X, designed by Hiden Analytical (referred to as "Hiden", henceforth). It is a candidate QMS on the diagnostic residual gas analyzer (DRGA) system currently being designed for ITER, the largest fusion machine (tokamak) being built.

The quadrupole comprises four parallel, conductive rods which modulate an electric field within the spatial aspect of the local region. It is created by applying voltages of both direct current (DC) (in a bi-polar arrangement) and alternating radio frequency (RF).

The static DC and alternating RF voltages are coupled and amplified (at ~1:6 ratio) in a manner that discretely allows ion masses to pass through the quadrupole in an ascending order while others are deflected away from the internal flight path as influenced by the time-dependent, voltage conditions during a mass scan cycle. Therefore, the probable outcome of an ion trajectory (as either a complex throughput transmission to the detector or a terminal collision path to a rod) depends on both the time at which a discrete ion mass is accelerated into the quad region relative to the exact conditions of both the amplified field and the effect from the polar state of the rods (discussed further in this section).

Figures 1 and 2 (below) show the profile of the amplified voltages during a mass scan as a correlation to both time and ion mass as well as the propagation of the oscillating electric field. The field intensity is proportional to the amplification during the scan cycle.

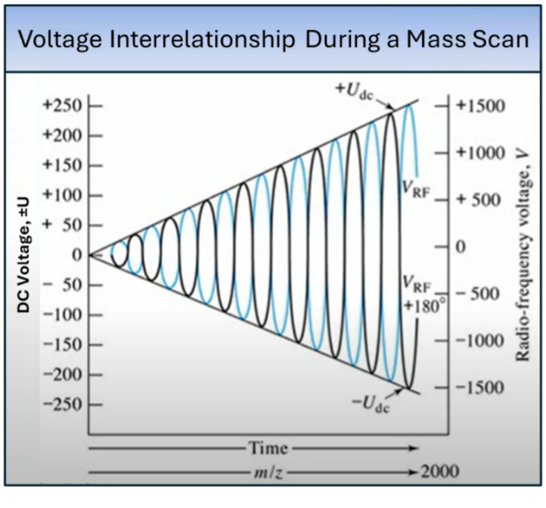

Figure 1. The graph shows the amplifying fields relative to a time (or ascending ion mass scan, m/z) cycle analyzed during a scan cycle. (*Image c/o Dr. David Kreller Chemistry Video:* *https://www.youtube.com/watch?v=aYOCb6GnXio*.)

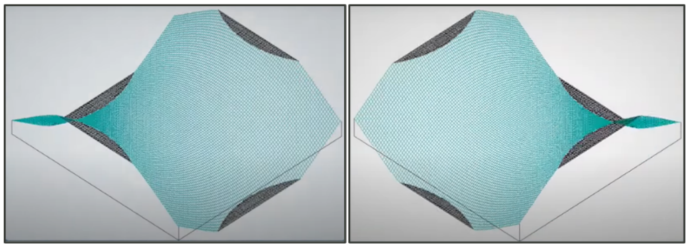

Figure 2. The conceptual images show the oscillating intensity of the electric field (typically within the 1-1.5 MHz range) within the quadrupole region during a scan cycle. It has a hyperbolic geometry (i.e., quadrupolar). (*Image c/o Waters Corporation Video:* *https://www.youtube.comc/watch?v=6_mavZ_WKoU*.)

The physical arrangement (i.e., planar alignment around the central axis) of the four rods and machining tolerance for both the linear and radial dimensioning are critical to ensure the cross-sectional aspect is a true orthogonal geometry. Adherence of the assembly, which is secured and electrically isolated using highly machined (i.e., to well-defined specifications), ceramic plates is also essential to ensure the quadrupole design will create a stable electric field and achieve the expected ion mass resolution in balance with the signal intensity. Figure 3 (below) shows the proper arrangement.

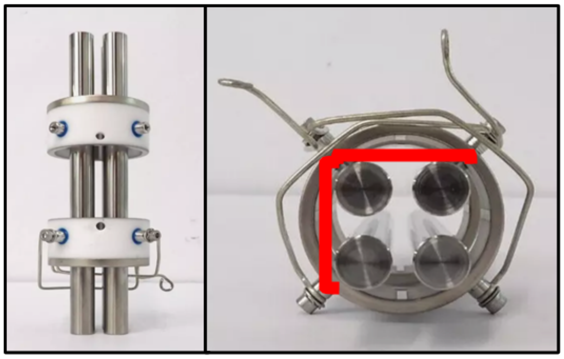

Figure 3. The paired photos show the quadrupole pole assembly, secured and electrically isolated by precision-machined, ceramic insulators, in proper planar alignment. The cross-sectional view shows the orthogonal arrangement (as indicated by the red outline) along a central axis. This geometry ensures the resolving power of the quadrupole is optimized for meeting performance specifications . (*Photos obtained through Google Image Search, April 2025: "Quadrupole Mass Filters"*)

The electric field within the quadrupole space is determined using the Cartesian (or "Rectangular") Coordinate System where positions (x, y) for points of stability are plotted. The accumulated regions represent the ratio of the two voltages. There are areas formed where these points form intersections and are determined to be stability zones (i.e., where ion motion does not extend beyond the inner space confined by the quadrupole) for setting the DC and RF voltages of the generated electric field. (NOTE: The mathematical solutions for determining the points of stability are a complex topic and beyond the scope of this paper.)

Figure 4 (below) shows the relationship between points in the coordinate system and the regions of intersection, which derive the voltage settings for a stable, electric field within the quadrupole. The highlighted area (nearest the origin) is known as the "First Stability Region" or "Zone 1" and is most often selected for the power since it allows for the lowest ratio settings and provides the largest area (or range) for selecting the field intensity. Therein, a standard resolution of 1 amu for mass separation can be achieved.

Figure 4 also shows a smaller stability zone (encircled, known as the "Third Stability Region" or "Zone 3"), which might be sustained at higher voltages, but it is more challenging in terms of sustaining a regulated field within that area. For comparison, Zone 1 yields a higher signal intensity (at a lower resolution of 1 amu) compared to the latter zone because more of the now concentrated ion masses are rejected, thus realizing a higher performance in resolving power.

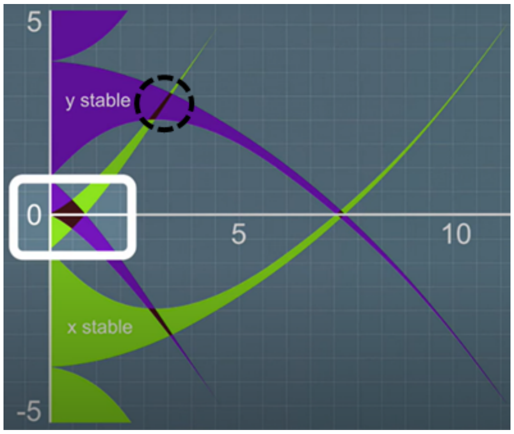

Figure 4. The plot of the electric field coordinate system (x, y) shows where the accumulated points of the voltage ratio form regions which form intersections to produce stability zones for a limited range of voltage settings to form the electric filed within the quadrupole. (*Image c/o Waters Corporation Video:* *https://www.youtube.comc/watch?v=6_mavZ_WKoU*.)

With the Zone 1 preference selected, it is known that the acquisition of the ion mass signal depends upon the quadrupole voltages. However, the signal intensity is dependent on the position setting of the voltage scan line (VSL) during the mass scan. The VSL sets the balance between sensitivity (i.e., ion current throughput for the scanned ion mass relative to the coinciding amplified voltages), which is the Y-coordinate of the scan and the resolution of the ion mass number, which is the X-coordinate of the scan. Therefore, the amplifying DC voltage is correlated to the ion current intensity while the amplifying RF voltage is correlated to the ion mass number for any given increment within the full mass scan.

Adjustments to the VSL allow the line to raise or lower the line intersection crossing through the amplifying DC voltage intensity (correlated to the ion mass signal detected by the analyzer) to realize uniform resolution and sensitivity adjustments across the full scan bandwidth. Also, the VSL slope can be adjusted for a local effect within a region of this bandwidth. For the latter tuning, a better resolution can be achieved in one region (e.g., the low-amu ion masses) while sacrificing signal detection for the higher amu ion masses (throughput conditions more stringent). Figure 5 (below) illustrates the position of the VSL relative to the intersection through the amplified DC voltage. Also, in essence, the amplifying RF voltage equates to the ascending ion mass number, also referred to as the "m/z" value.

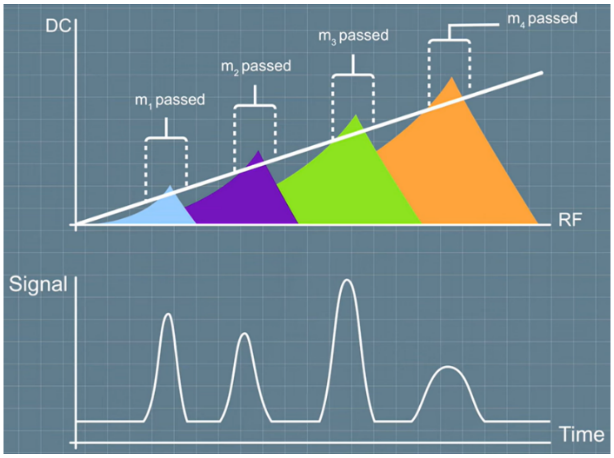

Figure 5. The two graphs show: 1) relation of the VSL to the intensity of the DC voltage, whereby the detected ion mass signal is dependent on the position of the line intersection during voltage amplification cycle (top graph) and 2) correlation of the DC and RF voltages to the detected ion current for the respective ion mass number (bottom graph). The VSL crosses the ascending stability regions for the increasing ion mass number to generate the signal intensity of the respective ion currents to generate a profile plot versus time (i.e., the mass spectrum profile). (*Image c/o Waters Corporation Video: https://www.youtube.comc/watch?v=6_mavZ_WKoU.*)

When encapsulating the fundamental terms of the quadrupole (i.e., amplified DC and RF voltages, oscillating electric field, aligned rod polarity, VSL, and ion mass trajectory), it can then be described as a "double-mass filter." The rod pair biased by the positive DC potential focuses all ions onto the central axis of the quadrupole. However, the superimposed RF field creates a negative bias within each half cycle of the period. Light ions become defocused, and lose normal flight trajectory (i.e., diverge toward this positively charged pole pair) while heavy ions are not affected and, therefore, continue their focused trajectory (to the analyzer). This rod pair is a "high-pass mass filter."

The rod pair biased by the negative DC potential defocuses all ions from the central axis. However, the superimposed RF field creates a positive bias within the half cycle. Light ions are affected and become focused (to the analyzer) while heavy ions continue with a defocused trajectory (i.e., diverge toward this negatively charged pole pair) and are lost. This rod pair becomes a "low-pass mass filter."

For the acquired ion mass signals, the width of the band-pass (mass resolution) is determined by the ratio of the RF and DC potentials while the central mass (mass-to-charge ratio, m/z) of the band-pass is dependent on the magnitudes of the RF and DC potentials as the voltages are amplified during the scan cycle. With the quadrupole function fully explained, the subsequent sections, related to QMS testing, can be well understood.

EXPERIMENTAL AND RESULTS

As mentioned, the DRGA system is being developed for the ITER Project. ITER is a magnetic confinement type (tokamak) fusion plasma reactor under construction in Cadarache, France. The DRGA system consists of instrument hardware to measure gas particle concentrations using both mass and optical spectroscopy techniques. (NOTE: The latter method is outside the scope of this paper.). For fusion, the primary region of interest (ROI) consists of the isotopes for hydrogen (H_2) and helium (He). For the former, this includes fusion-fuel gasses: tritium (T_2) and deuterium (D_2); for the latter, this includes ^{3}He and ^{4}He, which are a D-T fusion reaction byproduct gases. The DRGA for ITER has unique features as a "rad-hardened" design to ensure adequate immunity to both high-energy, ionizing radiation and high intensity, fringing fields.[1]

Neon (Ne) is also a candidate gas for analysis. Neon is one of the gases injected into the fusion plasma exhaust region, called "the divertor". It functions as a radiator to dissipate energy, originally generated in the fusion core, as the plasma flows into the divertor and interacts with material surfaces there. This energy radiation then prevents components from overheating. It allows for more stable operation of the plasma device by keeping the core hot and the exhaust region of the divertor boundary cool.

There are ITER-defined performance requirements for the DRGA subsystem (e.g., related to measurement sensitivity, response time, ROI) and challenges for the achievement thereof.[2] For example, one of the specifications calls for the detection of ^{4}He (relative to D_2) to a 10% concentration and at an accuracy at 20% or better. Additionally, the signal acquisition and data processing for this information must occur within a 1-second time increment. This information can be used in providing feedback for fueling and/or control of the ITER device.[3]

The accomplishment of these measurements, when considering the high sensitivity achievement versus the mass separation between the two analytes (0.0260 amu), is not an elementary task. The standard, commercially available QMS-RGA (also, referred to as "instrument", henceforth) has a mass solution of 1-amu (or "unit resolution") and, therefore, does not have sufficient resolving power to identify D_2 and ^{4}He.

However, Hiden has developed a specialized instrument, the HAL 101X, with unique RF circuitry which effectively sets the VSL to a steeper slope whereby a mass resolution of ~0.01 amu (peak width) is achievable. The specialized RF power supply (PS) applies the alternating voltage to the quadrupole to set the mass filter into what Hiden refers to as the "Zone H™" stability zone (or more commonly known as "Zone 3"). With the increased resolution achieved with the VSL adjustment, the amu bandwidth for the full scan is reduced. In this instrument, the mass range is compressed to 1-22 amu. (NOTE: Further discussion into intrinsic instrument details is both beyond the scope of this paper and also considered proprietary information.)

At Oak Ridge National Laboratory (ORNL), a production version of this specialized instrument was tested. It is further unique in that the electronics for the mains (for AC-DC rectification) and the enhanced RF (for the quadrupole) power supplies are remotely located with cabling sets of ~140 meters (420 feet) to simulate the displacement distance for the DRGA systems being developed for ITER. This displacement length is an advancement from an earlier prototype version of the Hiden QMS set at ~80 meters and successfully operated on the Joint European Tokamak (JET) several years ago.[4] The remote placement for electronics is needed due to the surrounding, harsh ionizing radiation environment. One DRGA system for ITER will be connected to an equatorial gas sampling port; the other, to a divertor sample port.[5]

The paired photos shown in Figure 6 (below) show the specialized instrument and the multiple cable reel series for the distance of the signal transmissions between the power supplies (PSs), the RF matching unit (not shown), and the plug connector to the instrument.

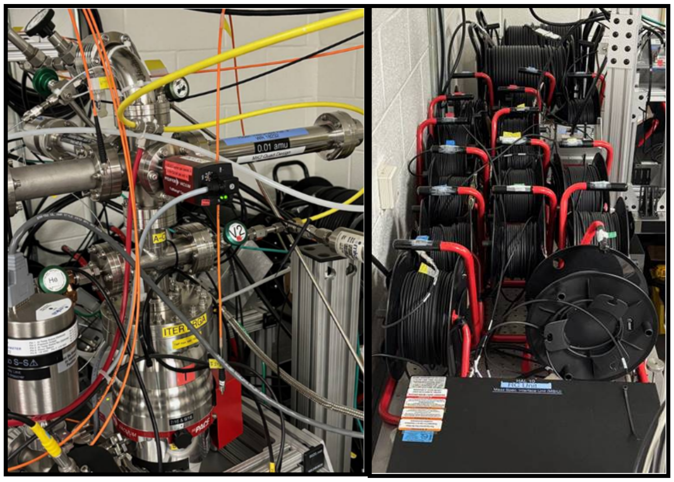

Figure 6. The left image shows the configuration of the Hiden HAL 101X QMS (far right) connected to the analysis chamber of the test stand at ORNL. The right image shows the reel sets of cabling interconnecting the PSs and the instrument plug for the QMS.

To initially test this instrument, a certified, mixed-gas leak consisting of ^{4}He and D_2 at a 3:97 concentration was analyzed to validate the performance needed. Before showing the resulting scan and discussing the calculation for determining the relative concentration value, an understanding of the derived mathematical expressions used is necessary.

Two important parameters used to calculate the ^{4}He concentration (relative to D_2) are referred to as the "R" and "RS" values. "R" is a ratio of the peak (or maximum) ion currents for the two ion mass species as acquired during a scan cycle and "RS" is a ratio of unique, gas-specific sensitivity factors, "S" (relative to nitrogen), for these two gases. The S values were obtained from the gas reference library for the Hiden instrument, which is accessible through the local controller software interface, MASsoft™.

Since there is not an available S for D_2, it was initially calculated at the Hiden test facility using a 50:50 mixture of the two gases to acquire the ion currents (inserted below). The S is typically expressed as follows:

S = Current (in Amps)/Pressure (in Torr)

Since the S term equates to the ratio of the peak ion current divided by the partial pressure (within the analysis chamber), then the ratio of the two S's can be expressed as RS, for D_2 relative to ^{4}He, as follows (where the pressure terms cancel due to 50:50 mixture):

$$RS_{D2:He-4} = \frac{S_{D2}}{S_{He}} = \frac{I_{D2}}{I_{He}} \cdot \frac{P_{He}}{P_{D2}}$$

$$RS_{D2:He-4} = \frac{6.6 \times 10^{-11}\ amps}{2.6 \times 10^{-11}\ amps} \cdot \frac{50\%_{Total\ Pressure}}{50\%_{Total\ Pressure}} = 2.5$$

With the RS value expressed as the ratio of S values and the quadrupole set to Zone H™ for the QMS scan, the relative ^{4}He concentration (mixed with D_2) can be determined when combined with the expression for R, as follows:

$$R = I_{D2}/I_{He\text{-}4},\ or\ I_{D2} = R{*}I_{He\text{-}4}$$

Then the expression of S is rewritten to define pressure as follows:

$$P_{He\text{-}4} = I_{He\text{-}4}/S_{He\text{-}4}, \text{ and } P_{D2} = I_{D2}/S_{D2}$$

Or expressing the ratio with a substitution as follows:

$$P_{He\text{-}4}/P_{D2} = (I_{He\text{-}4}{*}S_{D2})/(R{*}I_{He\text{-}4}{*}S_{He\text{-}4})$$

Then,

$$P_{He\text{-}4}/P_{D2} = RS/R$$

And,

$$RS = P_{He\text{-}4}{*}R/P_{D2}$$
$$\%^4He = 100{*}P_{He\text{-}4}/(P_{He\text{-}4} + P_{D2})$$

Then, with term substitutions,

$$P_{D2} = P_{He\text{-}4}{*}R/RS$$

Finally,

$$^4He\% = 100{*}1/(1{+}R/RS)$$

With the formula derived for calculating the ^{4}He concentration and the RS value obtained, the QMS was ready to commence with analyses of the leaks to compare to the known concentrations of ^{4}He and D_2.

The leak analyses were performed using the Hiden HAL 101X in Zone H™ settings while controlling the function using MASsoft™ to analyze the acquired scans. Since the ROI was within the narrower 1-22 amu bandwidth, the scan settings were reduced even further (e.g., within the 3.5 – 4.5 amu range). When the quadrupole is set for Zone H™ operation, the mass alignment becomes an arbitrary scale, although the relative, peak-to-peak mass separation (Δm) remains consistent with the difference in the mass numbers.

The first gas mixture to analyze was a 3:97 ($^4He:D_2$) leak. This gas source was produced by a third-party as a certified leak. Validation testing needed to be performed with this leak to formally accept the HAL 101X as a satisfactory QMS option for the ITER DRGA Project.

Figure 7 (below) shows one of the resulting scan cycles with the deconvolution of the ion mass signals for ^4He and D_2 verified. (NOTE: The test stand has a unique high-vacuum pumping section developed to prevent the back streaming of light gases, as is the ROI in the analyses discussed herein. This concept avoids a latent signal contribution to the real time analysis by the DRGA spectrometer suite to avoid biased concentration calculations.)[6].

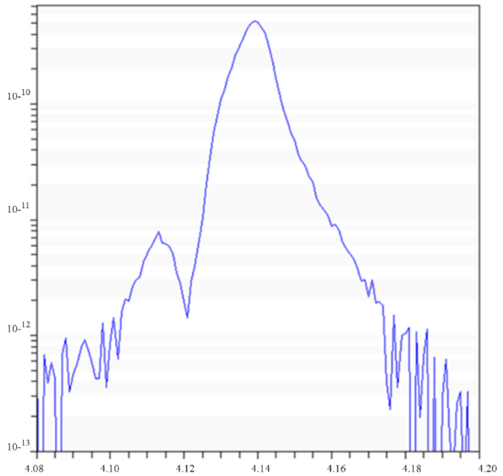

Figure 7. A profile scan performed at ORNL showing the resolved, raw ion current signals for ^4He (left peak) and D_2 (right peak) from the 3:97 leak analysis. The analyzer used was the secondary electron multiplier (i.e., "SEM") since the signal sensitivity is too low for detection by the Faraday Cup and, therefore, needs amplification (x1000).

The algorithm used in the MASsoft™ recipe calculated the ^4He concentration as 3.4% (~88% accuracy). The recipe run consisted of both a profile scan (to identify the two mass peaks, or "channels") and single ion detection scans (to acquire the ion currents of ^4He and D_2 from the channels identified in the former scan) to calculate the R value. This result validates the QMS measurement, using the HAL 101X in Zone H™ settings, meets the ITER requirement for ^4He sensitivity to within the level of accuracy (≥80%) of the true (known) value.

For DRGA prototype testing, ORNL has the capability to produce gas mixtures of arbitrary concentrations. This mixed-gas system was also used to generate a 3:97 leak to test the Hiden. The results from MASsoft™ calculated the ^4He concentration to be 3.2% (~94% accuracy). This task was conducted as part of the scope of testing for this QMS to document and report the acceptance validation process to the US ITER organization, which is responsible for managing the DRGA Project.[7]

Further testing was then conducted to determine if the assumption of the RS being of constant value versus dependence on other variables (e.g., leak composition, leak concentration, sampling pressure) is valid. The RS was calculated by rearranging the equation for the ^4He percentage to the following expression:

$$RS = R*f_{^4He}/(1-f_{^4He})$$

To accomplish this task, a series of leaks of both the original ^4He and D_2 composition as well as with the additive gas, Ne, were prepared (of various gas ratios), using the gas mixing station. Once the DRGA prototype analysis chamber was charged to a steady pressure, each leak was analyzed exclusively with the QMS. The results are summarized graphically in both Figures 8 and 9.

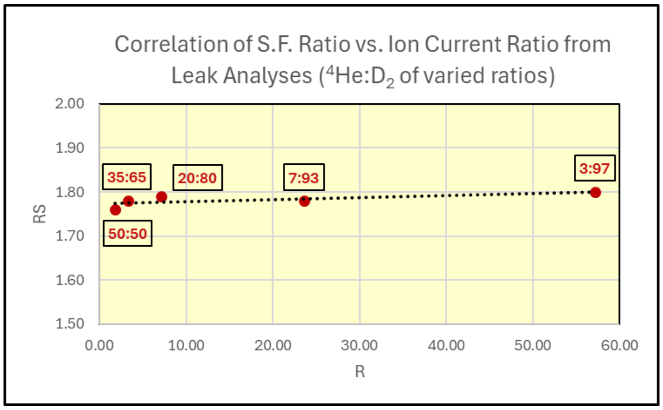

Figure 8. The graph shows the statistical agreement of the $RS_{avg.}$ values in the five data points plotted ($\sigma = 0.01$, $\mu = 1.78$). The value range was between 1.76 – 1.80. Therefore, it is reasonable to assume that a constant value is acceptable in calculating the $^4He_{rel.\ conc.}$ in a D_2 mixture.

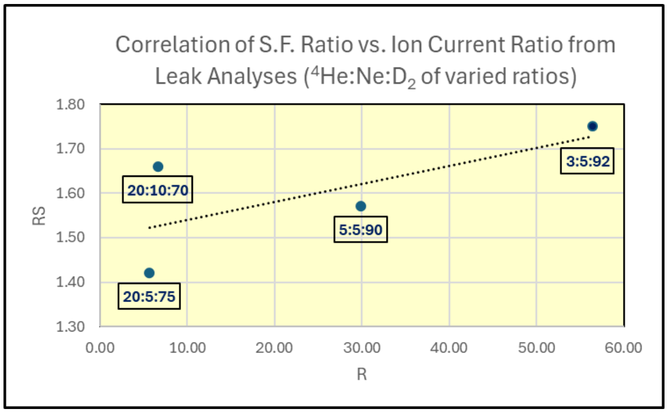

Figure 9. The graph shows the statistical variability of the $RS_{avg.}$ values in the four data points plotted ($\sigma = 0.14$, $\mu = 1.60$). The value range was between 1.42 – 1.76. Therefore, it is unreasonable to assume that a constant value is acceptable in calculating the $^4He_{rel.\ conc.}$ in a D_2 and Ne mixture.

It is noted that the original RS value (2.5) decreased when determined in subsequent testing (1.8). This can be attributed to changes in the some of the key parameter settings for the QMS associated with, among other components, the ion source and the VSL. This also may be caused by the onset of the expected instrument degradation due to the accumulated time of usage during this period of testing. These matters should be evaluated further during the expected additional testing of this QMS.

Data for over twenty gas leaks comprising nine, unique mixtures, for both ^{4}He and D_2 (5 mixtures) and ^{4}He, D_2, and Ne (4 mixtures), were analyzed by the QMS scans. The sample pressures (gas-corrected) were in the E-6 decade (mbar) except for one (low E-5 mbar). (NOTE: A higher pressure was selected for one scan to determine if the RS value is affected by pressure, which did not appear to be a factor.) The number of scans per analysis was ≥ 9 while, overall, the RS_σ was ≤ 1.

Of importance to note, relative to the Ne ion current measurement, is that there is another gas in the ITER ROI, D_2O (or deuterated water vapor), which causes interference in resolving either gas with the QMS set in Zone 1. The mass difference between Ne-20 (19.992 amu) and D_2O (20.028) is 0.036 amu. If present in a leak mixture, it would have an identified peak at ~20.339 amu when viewed from the aspect of the arbitrary mass scale (+ 0.311 amu offset) using Zone H™, as shown in Figure 10 (below). Therein, it is reasonable to assume that D_2O could also be detected/measured satisfactorily, and to within a comparable concentration to ^{20}Ne, with the QMS.

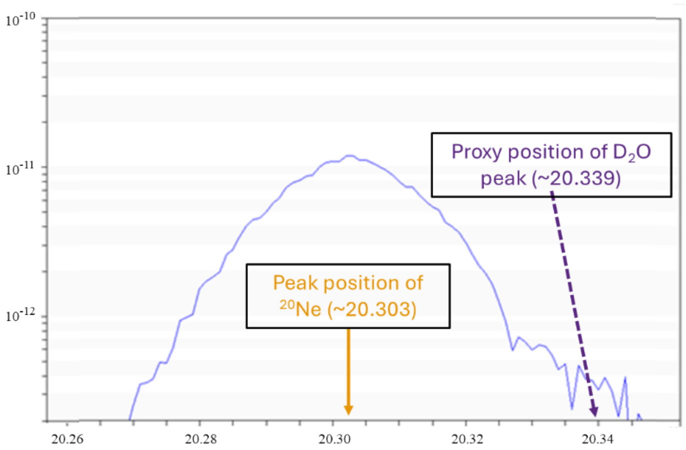

Figure 10. The image shows the signal intensity measured from MASsoft™ of ^{20}Ne from the QMS scan in Zone H™ settings. The resolved intensity is from measurement of the 3:5:92 (^{4}He:Ne:D_2) leak. Like the scan image shown earlier for the resolution of ^{4}He in a D_2 matrix (see Figure 7), the mass scale is arbitrary. The graphical view shows the index for the D_2O peak.

DISCUSSION

The data analyses, which comprised testing of the Hiden HAL 101X QMS to understand both the effectiveness of resolving power for deconvoluting low-amu ion masses and the effects of concentration and composition variations to the RS value, yielded preliminary results. More, related tasks will be undertaken to confirm both the reliability and repeatability of what has been discussed herein. Also, the subsequent testing will be performed under a larger scope which will also include the optical emission spectroscopy diagnostic tool[8]; also part of the ITER-DRGA design basis.

Two, possible solutions for avoidance of miscalculations in determining the ^{4}He concentration, caused by variants in the RS value not yet fully understood (i.e., due to effects from varied concentration and composition of analyzed, mixed-gas leaks) are being included in a larger scope of testing for this DRGA Project to 1) approximate a nominal RS value, as determined optimal for the range of ^{4}He concentrations predicted from modeling of the ITER system (e.g., predictions in fueling efficiency, gas flow modeling, and reaction kinetics) or 2) compile a library correlating the values of RS versus R from the analyses of the known ^{4}He concentration in specific leak mixtures. Subsequently, when the DRGA system is used to acquire the ion currents from sampled gas during ITER operations, the R value can be calculated from ion current measurements and used as an input to acquire the appropriate RS value stored in a software subroutine native to the ITER control architecture for this system. Regardless of the preferred option, it cannot be overstated that the RS value is dependent on QMS parameter settings (e.g., source filament emission current, cage bias voltage, analyzer bias voltage), whereby if input changes are made, then the value will need to be reevaluated within the scope previously discussed.

Regarding a phenomenon related to a shifting of the mass peak alignment (a few thousandth of an amu, while the relative mass separation remained constant) was noted when the quadrupole operated with Zone H™ settings, it is believed (from discussion with Hiden) that the root cause is associated with fluctuations in the ambient temperature whereby the resistant in the primary RF circuit changes, which then affects the output of the alternating voltage to the quadrupole, which then slightly alters the stability state of the electric field.

There are two enhancements to the QMS operation, related to both hardware conditioning and the MASsoft™ scan settings, which can likely resolve this anomaly. The first action would be to contain the RF PS module in a temperature-controlled box whereby the internal temperature is 15-20 degrees higher than the monitored ambient temperature in the feedback control circuit. The other solution would entail adding two, additional channels to the peak scans, for each of the ion masses in the ROI, to "bookend" the center-most peak channel (as determined in the analysis of the calibrated gas leak). Then, the ion current intensity for each of these masses would be expressed as the average of the three channels acquired in the scan, which then becomes the summed value for determining the R value, as previously addressed.

CONCLUSIONS

The QMS mass filter, the quadrupole, comprises an intricate design when considering the tight tolerances for both mechanical assembly and voltage regulation to create a uniform, stable electric field. It is the most important component in the spectrometer because it controls the ion mass throughput between the ion source and the detector. This function is realized by designing the amplification of the applied DC and RF voltages to align with the determined stability zones where the voltage regions intersect. In this manner, the motion of ion trajectories is confined to within the quadrupole for selective throughput as affected by attractive and repulsive forces of the DC-biased quadrupole rods. The passing ion current is then

ISSN 0737-5921
ISBN 978-1-878068-45-3

acquired for the measurement of intensity for scanned masses.

The R and RS values, which represent ratios of ion current and gas ionization sensitivities, are the key parameters to calculate the relative gas concentration (e.g., for ^{4}He in D_2. In preliminary testing of varied, known leaks, the RS value was determined to be reasonably constant. However, significant variation was noted when a third gas, Ne, was included in the gas mixture. This phenomenon needs further analysis, relative to varied gas concentrations (and, ultimately, selection of any calibration gases for the DRGA system configuration), to control the variance appropriately and make the DRGA an effective resource to acquire the measurements of the neutral (exhaust) gas composition within the ROI for ITER.

ACKNOWLEDGEMENTS

The lead author extends appreciation to the US-ITER DRGA Project team at ORNL; especially, Chris Klepper and Brendan Quinlan for insightful conversations related to the overall progression of collaboration with Hiden Analytical to realize the performance testing achievements. Overall, the team contributions have been essential for sustaining the described laboratory test stand for applied plasma diagnostics research.

Additionally, gratitude is extended to Hiden Analytical; specifically, to Mark Buckley and Luke Levin-Pompetzki for their continual support in sustaining an effective and continual collaboration for testing as related to the specialty QMS described in this paper.

This work was supported by the United States Department of Energy (DOE under Contract No. DE-AC05-00OR22725.

REFERENCES

[1] B.R. Quinlan et al., “Design Considerations to Ensure Robustness of the ITER Diagnostics Residual Gas Analyzer,” in IEEE Transactions on Plasma Science, PP(99):1-6, Jan. 2024 10.1109/TPS.2024.3387443

[2] P. Andrew (IO/DG/ENGN/EDD/PPD/IVD), “Sub-System Requirement Document sSRD-55.G4: RGA ”, 05 (Version 1.5), May 2022

[3] C. C. Klepper et al., "Feasibility of Fusion Plasma Burn Control via Real-Time, Sub-divertor Neutral Gas Isotopic and Compositional Analysis,” in Nuclear Fusion, Vol. 65, No. 8, pp. 1-17, July 2025 doi.org/10.1088/1741-4326/ade9dc

[4] C. C. Klepper et al., " Preliminary demonstration on JET of an ITER neutron environment-compatible quadrupole mass-spectrometer," in IEEE Transactions on Plasma Science, Volume 170, September 2021 doi.org/10.1016/j.fusengdes.2021.112672

[5] C. C. Klepper et al., "Developments and Challenges in the Design of the ITER DRGA," in IEEE Transactions on Plasma Science, Vol. 50, No. 12, pp. 4970-4979, Dec. 2022 10.1109/TPS.2022.3223648

[6] C. Marcus et al, “Eliminating Signal Bias Caused by Vacuum System Backstreaming in the Diagnostic Residual Gas Analyzer for ITER,” Society of Vacuum Coaters, Nov. 2024 doi.org/10.14332/svc24.proc.0035

[7] C. Marcus, Measurement Acceptance Report for the Hiden HAL 101X RC Quadrupole Mass Spectrometer (QMS) WR18232 for DRGA (55.G4 Diagnostic Residual Gas Analyzers), Document ID: 808d398d - 1.0, September 2025

[8] D. L. Hillis et. al., Tritium Concentration Measurements in the Joint European Torus Divertor by Optical Spectroscopy of a Penning Discharge,” Review of Scientific Instruments, Vol 70, pp. 359–362, January 1999 doi.org/10.1063/1.1149301

FOR FURTHER INFORMATION

The lead author, Chris Marcus, is a plasma diagnostics researcher at the Oak Ridge National Laboratory; managed and operated by the United States Department of Energy. He can be reached through e-mail: “marcusc@ornl.gov.”