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RECEIVED: *June 27, 2019*
REVISED: *November 6, 2019*
ACCEPTED: *November 19, 2019*
PUBLISHED: *January 23, 2020*

3RD EUROPEAN CONFERENCE ON PLASMA DIAGNOSTICS (ECPD2019)
6–10 MAY 2019
LISBON, PORTUGAL

2020 JINST 15 C01032

Neutral gas analysis for JET DT operation

U. Kruezi,[a,f,1,2] I. Jepu,[b] G. Sergienko,[c] C.C. Klepper,[d] E. Delabie,[d] S. Vartanian[e] and A. Widdowson[a]

[a] *CCFE, Culham Science Centre, Abingdon, OX14 3DB, United Kingdom*
[b] *National Institute for Laser, Plasma and Radiation Physics, Magurele, 077125, Romania*
[c] *Forschungszentrum Juelich GmbH, Institut fuer Energie und Klimaforschung — Plasmaphysik, Juelich, Germany*
[d] *Oak Ridge National Laboratory, Oak Ridge, TN 37831-6169, U.S.A.*
[e] *CEA IRFM, F-13108 St Paul Les Durance, France*
[f] *ITER Organization, Route de Vinon-sur-Verdon, 13067 St. Paul-lez-Durance, France*

E-mail: uron.kruezi@iter.org

ABSTRACT: Neutral gas analysis, the measurement and evaluation of total and partial pressures, is a key technique to study the impact of neutral gas dynamics on retention, recycling and release processes of fuel or impurity species in fusion devices. At JET, the experiment closest to ITER in terms of operating parameters and size, various detectors and techniques for partial pressure and total pressure measurements are deployed together to characterise neutral gas dynamics during and after plasma operation on various toroidal and poloidal locations. An extensive modification of JET's sub-divertor neutral gas diagnostic system aims at retaining and extending established measurement capabilities in the forthcoming Deuterium-Tritium (DT) experiments (DTE2). To achieve DT compatibility, a separation of radiation-sensitive electronics from the sensor and adequate radiation shielding is required, as well as utilisation of a DT compatible differential pumping system with adjustable throughput to account for the strong pressure variation in the sub-divertor region. Finally, the sub-divertor neutral gas diagnostic will be equipped with multiple Residual Gas Analysers

[1]Corresponding author.
[2]Currently at the ITER organization.

https://doi.org/10.1088/1748-0221/15/01/C01032

(RGAs), utilising quadrupole mass spectrometry and electrostatic ion-trap-principles, all operating with remote electronics located behind the biological radiation shield. These RGAs will record data in a fast selected discrete mass mode during plasma pulses (cycle ~ 2 s) and will automatically switch back to continuous data recording (cycle ~ 100 s) afterwards. They will be complemented by a newly improved Penning gauge spectroscopy configuration in particular supporting the He and D_2 separation relevant for DT operation. The distance between these devices and their associated control unit is typically 15m . A newly developed RGA with a cable length of 80 m, compatible with the ITER environment, will also be employed for the first time. This set-up and its operation in DTE2 will provide vital input to the development of the ITER divertor RGA in the most relevant environment currently available.

KEYWORDS: Plasma diagnostics - interferometry, spectroscopy and imaging; Radiation-hard electronics

2020 JINST 15 C01032

Contents

1 Introduction **1**

2 General experimental arrangement **1**

3 The sub-divertor neutral gas diagnostic **3**
- 3.1 Total pressure measurement 4
- 3.2 Residual gas analysis measurement 5
- 3.3 Optical gas analysis measurement 6

4 Outlook **8**

1 Introduction

Neutral gas analysis, the measurement and evaluation of total and partial pressures is a key technique to study the impact of neutral gas dynamics on retention, recycling and release processes of fuel and impurity species. It contributes vital information to the characterisation of the edge plasma and wall conditions in nuclear fusion plasma experiments [1, 2]. Although the capability to monitor the vacuum conditions after a plasma discharge or to study outgassing of fuel or impurity species has been established on many experiments [3] the focus has shifted significantly in the last years towards time resolved measurements during plasma operation [4]. This is primarily driven by the fact that computer modelling codes and computational power enable accurate studies of the neutral gas dynamics for plasma scenarios [5]. The gas dynamics heavily influence plasma-wall interactions, or more precisely, the fuel recycling within operational regimes such as the detached divertor plasmas. This detached regime is building the base for plasma operational scenarios in ITER and beyond [6].

At JET, the experiment closest to ITER in terms of operating parameters and size, cold cathode ionisation gauges, total pressure gauges (capacitance manometers), Quadrupole Mass Spectroscopy (QMS) and optical Penning discharge spectroscopy are deployed together to characterise neutral gas dynamics during plasma operation. In combination with the active gas handling system at JET this has become an efficient tool to quantify many relevant processes for experiments in JET as described in the following.

2 General experimental arrangement

The JET vacuum vessel is equipped with a large number of toroidally and poloidally distributed detectors which can be utilised for neutral gas analysis. They can be grouped in partial and total pressure measurements, in Residual Gas Analysers (RGAs) or Optical Gas Analysers (OGAs). Their toroidal distribution is indicated in figure 1.

The robust and radiation hard (up to 1×10^7 Gy) cold cathode gauges *IKR060* with a measurement range of 1×10^{-10} to 1×10^{-3} mbar have been providing gas species dependent partial pressures during and in-between discharges for vacuum monitoring over the last few decades of the JET operation. Typically only four of these gauges (in two toroidal positions *Octant 1* and *Octant 5*) are also used for scientific studies such as the pumped particle flux in fuel retention studies [7]. This gauge type has been successfully used to characterise the vessel pressure during DTE1, which generated 2.4×10^{20} fusion neutrons and was the only method available for neutral gas analysis during and in-between plasma pulses. For the upcoming DT (DTE2) experiments, for which the produced neutron number is expected to be as high as 1.7×10^{21}, the toroidally and poloidally distributed sensors have been upgraded to survive and reliably operate during the high neutron fluxes (expected dose in the range of 7.37×10^4 Gy(Si)) and radiation (expected gamma dose 6×10^4 Gy(Si))). The expected dose rates in the torus area will practically permit no personnel access, already after a few DT plasma pulses, and therefore the reliability and survival of the measurement equipment is a key goal.

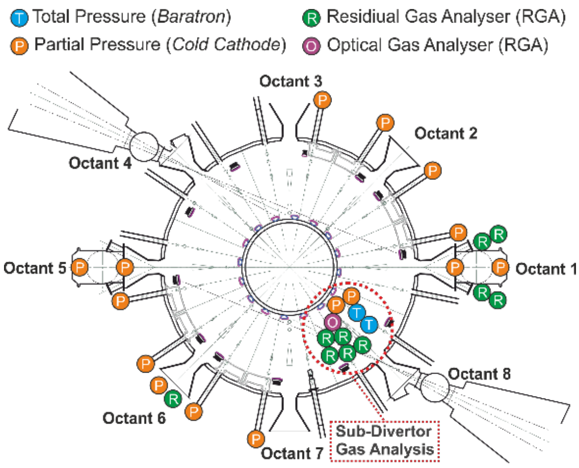

Figure 1. JET neutral gas analysis measurements.

For the DTE2 experiment, also potentially the last DT experiment worldwide before the first ITER DT phase (in the mid-2030s), most available pressure measurements (in 12 different toroidal

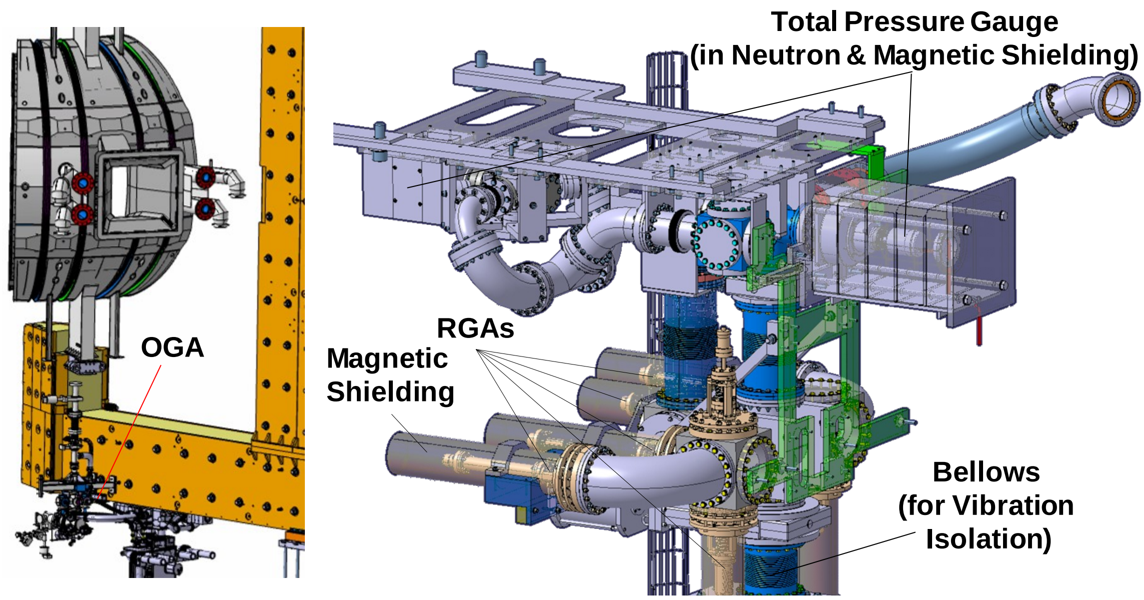

Figure 2. *(Left)* Sub-divertor gas analysis diagnostic location with respect to the JET vacuum vessel. *(Right)* RGA and total pressure measurement arrangement as located under the transformer limb.

locations as indicated in figure 1) and RGAs (in three toroidal locations) have been upgraded in terms of hardware, control software, operational strategy and their data made easily available.

To achieve DT compatibility a separation of radiation-sensitive electronics from the sensor, or adequate radiation shielding is required. Hence all relevant instruments with integrated active electronics have had been modified with (a) passive components (without electronics), (b) electronics adapted to the expected radiation and neutron environment (utilising radiation hard electronics e.g. vacuum tube based) or (c) electronics located remotely (behind the JET bio-shield (100mm deep boronated concrete walls)) or inside dedicated radiation and neutron shields. In the frame of these upgrade measures, particularly the JET sub-divertor neutral gas diagnostic has undergone a substantial modification to keep and extend the successful measurement capabilities in terms of total pressure, RGAs and OGAs throughout the DT operation phase.

3 The sub-divertor neutral gas diagnostic

The sub-divertor neutral gas analysis (JET internal name *KT5*) has been implemented and utilised for measurements at JET for over 30 years. Its original focus was on Penning gauge spectroscopy measurements [8, 9], operating as *Optical Gas Analysers*. This system delivered reliable data over decades.

The functionality after the recently completed extensive modification as shown in figure 2, during which the entire vacuum chamber and vacuum pumping system of the original diagnostic has been re-newed and hardware added particularly designed to operate throughout the DTE2 phase, can be seen in the P&ID in figure 3. In order to achieve a reliable *Total Pressure Measurement* which is particularly susceptible to vibration at low pressures, vibration damping has been incorporated into the design. Bellows are used to decouple the detectors and vacuum chamber from all surrounding

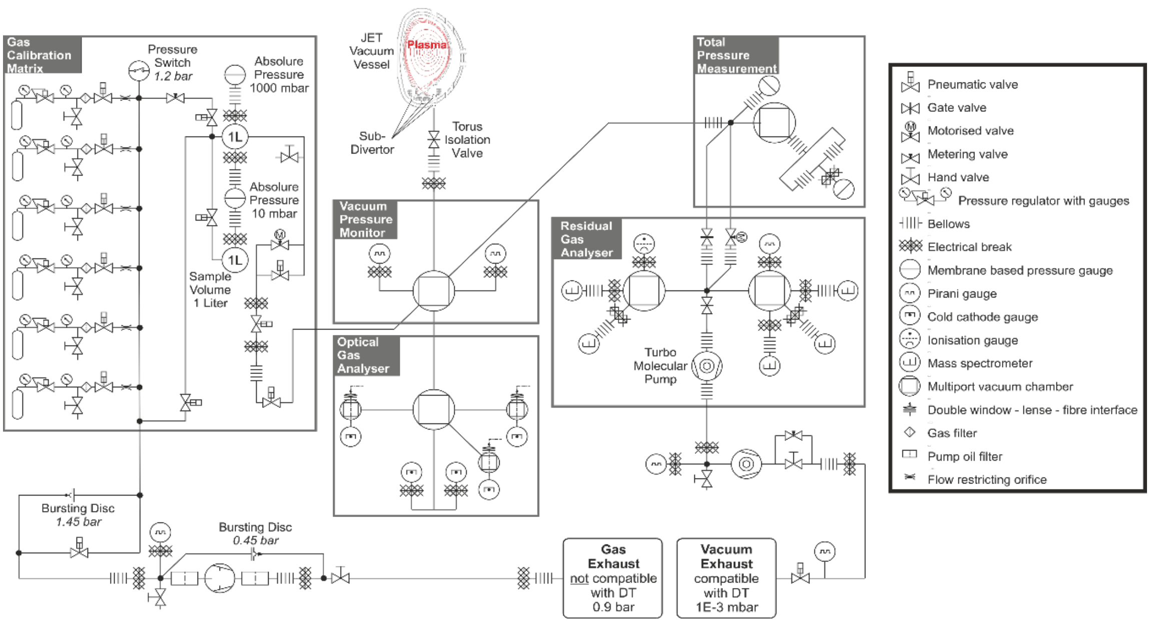

Figure 3. Sub-divertor gas analysis diagnostic Piping and Instrumentation Diagram (P&ID).

2020 JINST 15 C01032

plant in order to obtain the minimum resolvable total pressure. Since the pressure in the sub-divertor region can vary from 1×10^{-6} mbar up to 5×10^{-3} mbar during the discharge and lower than 1×10^{-7} mbar after the discharge, it is necessary to control the conductance between the main diagnostic chamber and the *Residual Gas Analyser* components which typically require sample gas pressures in the range of 1×10^{-5} mbar to operate reliably. This has been realised by implementing a DT compatible differential pumping concept. This system is composed of a motorised needle valve controlled by a radiation hard stepper motor in combination with a resolver (instead of the typically used optical encoders), an accurate ionisation pressure gauge and two turbo pumps in series to exhaust tritiated sample gas. In order to commission and ensure consistency between the acquired signals throughout the DTE2 operation a dedicated *Gas Calibration Matrix* will be employed. In the following sections the total pressure measurement, residual gas analysis and optical gas analysis systems are described.

3.1 Total pressure measurement

In 2011, after JET started operation with the new ITER-like-wall the sub-divertor region was equipped with total pressure gauges for gas species-independent pressure measurements during discharges [10]. They were successfully used to calibrate and verify the cold cathode measurements of the JET vacuum vessel. In addition they were utilised scientifically, to characterise the recycling flux at the cryogenic pump in the JET divertor along with gas flow modelling [13, 14]. This was an essential step towards a better understanding of plasma exhaust and demonstrated the potential for future applications such as real time pressure controlled divertor detachment.

As part of the recent upgrade a few modifications were implemented to ensure reliable operation during the DT operation but also to improve the performance. Currently there are no total pressure gauges with the required performance and remote electronics commercially available, therefore two *MKS 627D* 0.1 mbar Baratrons were installed. These gauges have built-in active electronics and have been located in the shadow of the JET transformer limb (as shown in figure 2) and equipped with a modular neutron shielding consisting of borated polythene blocks with internal radiation and magnetic shield (soft iron tube) as shown in figure 4. Nuclear analysis shows that the expected neutron silicon dose with this shielding and the device position is 3.85×10^{-1} Gy(Si) compared to the case without shielding where a dose as high as 1.92×10^{2} Gy(Si) would threaten the operational lifetime of the integrated

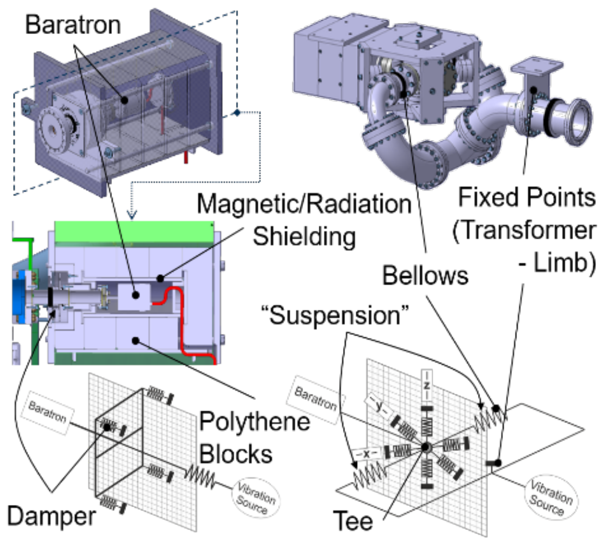

Figure 4. *(Left)* Standard *(Right)* Enhanced vibration damped total pressure gauge for improved low vacuum pressure resolution.

electronics. To further improve the performance in the low pressure region two vibration damping concepts have been deployed. Where space was limited a compact "standard" design was used for one of the gauges for easier integration (see figure 4 (left)). In this setup elastic silicon vibration dampers were installed with an axial edge welded bellow which due to the atmospheric pressure generates a force which compresses the dampers. This vibration damping concept was originally designed for JET but has also been successfully used elsewhere [15]. A more enhanced vibration damping concept was developed for the second gauge (see figure 4 (right)) where the compression due to the atmospheric pressure is compensated by the mechanical setup. In the design two edge welded bellows act as a "suspension" enabling an arrangement of pneumatic vibration dampers (typically used for optical components which require good damping at low frequencies) oriented along the three spatial x-y-z axes around a vacuum tee attached to the gauge. The enhanced damping concept will typically result in better performance but requires a larger footprint and is therefore more difficult to implement when space is limited. This vibration damping concept enables pressure measurements down to 4.3×10^{-6} mbar, as initial commissioning of the system indicates, which is a factor of 1.6 lower compared to the original vibration damped gauge design [10].

3.2 Residual gas analysis measurement

For partial pressure analysis during plasma operations, JET has been equipped with five Diagnostic Residual Gas Analysers (DRGAs) in addition to the five standard JET vacuum integrity RGAs (see figure 1). Since the latter are not equipped with sufficient magnetic shielding, their data cannot be utilised for scientific neutral gas analyses during plasma pulses. The DRGAs are magnetically-shielded by a combination of a (450 mm) long open ended soft iron tube shielding against DC magnetic fields and an additional internal Mu-Metal shield tube for stray fields. Due to the presence of radioactive tritium in the sampling gas, all DRGA mass filters are continuously heated (∼ 150°C) to minimise local tritium accumulation and thus reduce beta decay induced noise in the filter. The sub-divertor neutral gas diagnostic is equipped with four types of RGAs. The latest design of an ITER QMS prototype (*HIDEN HAL7*) [16] with a 80 m long extension cable and local radiation hard vacuum tube based electronics is employed on a tokamak for the first time. Two similar standard QMS RGAs (*HIDEN HAL7*) suitable for ionisation threshold or normal 1–100 amu mass scans will be installed with remote electronics extensions of 15 m length sufficient to localise the active electronics behind the biological shield. One additional QMS RGA (*MKS MV2*) with a 15 m long extension cable will be installed in the same manner. This provides a comparison between the sub-divertor and other locations in JET as the five RGAs installed for vacuum integrity monitoring are also of this type. To complement the setup a different type of RGA (*MKS VQM835*) based on the fully electrostatic ion trap analyser

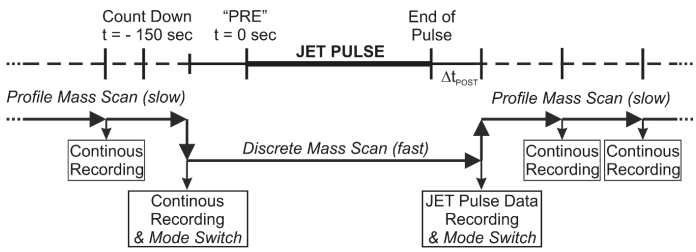

Figure 5. JET RGA operation with automatic mode switching for faster plasma pulse data. — All JET RGAs are equipped with this optional feature with all input parameters set by the user.

2020 JINST 15 C01032

method has also been installed. This type of analyser enables very fast scans at high mass resolution but with limited dynamic range and is installed with a 20 m-long (max. 50 m) cable.

These DRGAs have been implemented into the JET standard data acquisition and control system. The control hardware utilises a private network strategy in a point-to-point fibre based network configuration. A new RGA hardware type independent control scheme has been established based on a Human-Machine-Interface (HMI) with a generic RGA parameter list instead of the manufacture defined/named parameters. This enables components that become obsolete in the future to be replaced with another type without the need to modify the HMI. This control and data acquisition interface is based on HTTP/EPICS and has been implemented for all RGAs on JET. The collected data is handled in a multi dimensional data matrix to store mass signal intensities vs atomic unit masses and/or ionization energies and time stamps. The latter are synchronised with the JET time base with an accuracy better than 1 s. This new control scheme as indicated in figure 5 enables the standard continuous *Profile Mass Scans* between discharges (inter discharge time) with cycling times of typically 100 s over a wide range of masses (1–100 amu with 0.1 amu resolution) to be switched to a *Discrete Mass Scan* for dedicated masses, also known as *peak jump* mode. The latter enables a much faster cycling time (typically 20 masses in 2 seconds) during the discharge (intra discharge time). Peak drift in the intra discharge data (if any) is corrected using the inter discharge data. For this purpose the most recent *Profile Mass Scan* will be analysed to identify the actual position of the mass peaks and their amplitudes in the measured spectrum. This information is then used to correct the mass amplitudes of (discrete) masses measured during the *Discrete Mass Scan*.

This newly established data collection method provides immediate information after or during the plasma discharge about partial pressures crucial to dedicated experiments such as wall conditioning [17], ammonia quantification [18, 19] or wall conditions after massive gas injection [20]. In addition to the traditional mass scan application, the current hardware may be operated in a swept ioniser energy techniques at fixed masses. This could be utilised, e.g., to resolve deuterium (D_2) molecules from helium (He) atoms (present as fusion product during DT operation) both at an atomic mass of four or other same-mass species but with different ionisation thresholds. In separate laboratory tests a minority species of He in a D_2 background could be detected down to low concentrations using this method. Initial tests in JET plasma pulses with He trace injections are also promising [21]. However, since the development of this method for use in tokamaks is in its initial phase, an independent spectroscopic method will be employed to distinguish between He and D_2, as discussed below.

3.3 Optical gas analysis measurement

Although He and D_2 have very similar masses their spectroscopic characteristics are significantly different. The classic method to distinguish these in neutral gas is based on the application of optical spectroscopy on the plasma light emission originating from Penning ionisation gauges. The collected light is typically coupled (via optical fibres) to interference filtered photo detectors or high-resolution spectrometers. Utilising the latter, the JET set-up has been operating reliably for more than 20 years providing hydrogen to deuterium ratios in the sub-divertor and has delivered valuable information on helium compression and isotopic ratios during the first DT operation (DTE1) in 1997 [9]. The main limitation of measuring low concentrations with this method is the low level of acquired signals combined with the fact that optical components, such as windows lose transmission

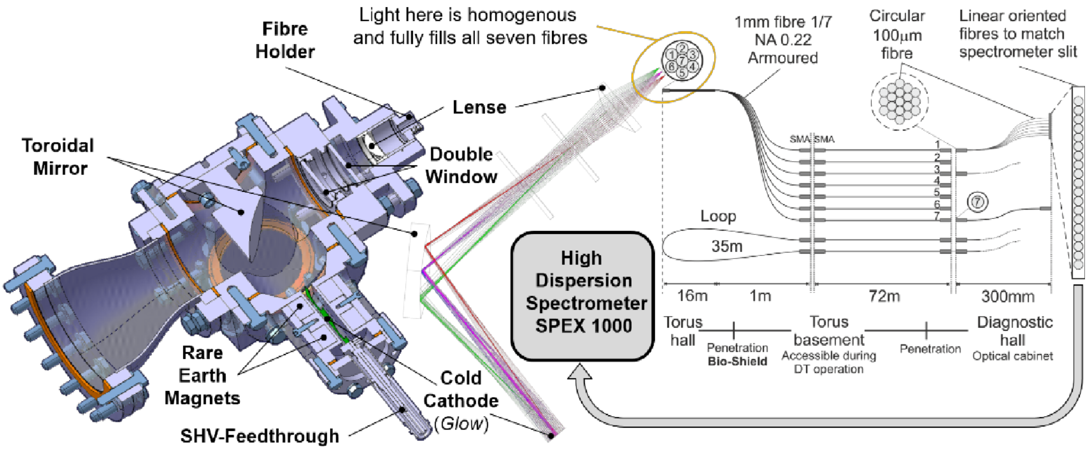

Figure 6. *(Left)* OGA 3D model and OGA optical design *(Right)* Light fibre and detection scheme.

due to build-up of deposits thus lowering the signal further. To significantly improve upon data collection a new OGA concept consisting of a special cold cathode gauge, a 6-way vacuum cube, an in-vacuum-toroidal-mirror and external collection optics have been developed and shown in figure 6 (left). This replaced the obsolete Alcatel CF2P gauges formerly used. This setup is based on a complete conflat vacuum flange design, a double window for vacuum interspace monitoring and an overall optically optimised design for maximum light throughput. The enhanced cold cathode gauge utilises the established discharge geometry of the CF2P gauge but with modifications to the light path in order to optimise the light output. Since in this setup there is no line of sight between the Penning discharge and the vacuum windows a long operational life time is ensured. In addition the choice of components and layout have been optimised to facilitate maintenance and refurbishment especially in tritium contaminated environments. A new one-to-seven fibre bundle concept shown in figure 6 (right) provides fully filled homogenous light from the Penning discharge and enables lossless sharing of signals on multiple detectors. Reference fibre loops are also installed to assess fibre darkening effects due to neutrons and radiation and allow for signal correction to be applied during DT operations. In order to determine the light intensity of a spectral line the spectral background must be reliably identified and subtracted. For the OGA this is done using a high-resolution spectrometer and adequate data fitting methods. For this purpose a high dispersion spectrometer (*SPEX 1000*) used previously has been equipped with a new ANDOR iDus 401 camera. Together this enables the resolution of Hα/Dα/Tα and 4He (667.815 nm) and 3He (667.865 nm) simultaneously in one spectrum as shown in figure 7.

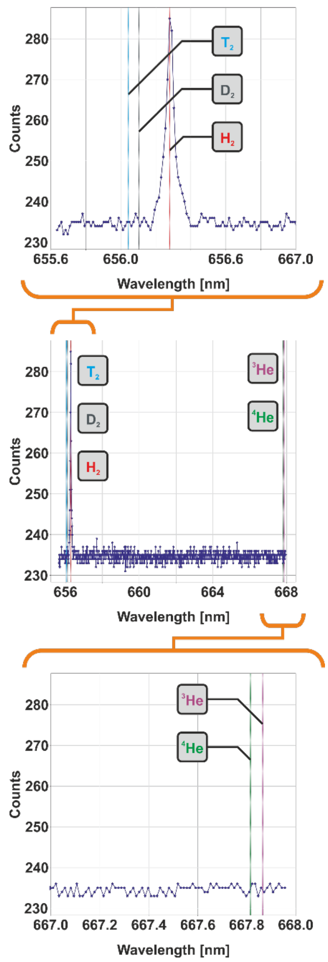

Figure 7. Recorded OGA spectrum (at a pressure of 8×10^{-5} mbar)

2020 JINST 15 C01032

The new OGA at JET is dedicated to hydrogenic species and helium and all other impurities will be monitored utilising RGAs. While the new OGA setup will be utilised to distinguish between these lower mass species , supporting the RGA measurements in this range, the RGA setup will exclusively be used for all other species with higher masses employing cracking pattern analysis [11, 12].

4 Outlook

The JET neutral gas analysis system of JET has been improved for the upcoming DT operation. In particular the newly upgraded sub-divertor gas analysis diagnostic with its new OGA and radiation hard RGAs, compatible with the ITER environment, will provide vital input to the development of the ITER DRGA [22] in the most relevant environment currently available.

Acknowledgments

This work has been carried out within the framework of the Contract for the Operation of the JET Facilities and has received funding from the European Union's Horizon 2020 research and innovation programme. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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