AIP | Review of Scientific Instruments

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Citation: Rev. Sci. Instrum. **83**, 10D728 (2012); doi: 10.1063/1.4732175
View online: http://dx.doi.org/10.1063/1.4732175
View Table of Contents: http://rsi.aip.org/resource/1/RSINAK/v83/i10
Published by the American Institute of Physics.

JET divertor diagnostic upgrade for neutral gas analysis[a)]

Uron Kruezi,[1,2,b)] G. Sergienko,[1] P. D. Morgan,[2] G. F. Matthews,[2] S. Brezinsek,[1] S. Vartanian,[3] and JET-EFDA Contributors[c)]
JET-EFDA, Culham Science Centre, Abingdon OX14 3DB, United Kingdom
[1]*IEF, Plasmaphysik, FZJ Jülich GmbH, Association EURATOM-FZJ, D-52425 Jülich, Germany*
[2]*Euratom/CCFE Fusion Association, Culham Science Centre, Abingdon OX14 3DB, United Kingdom*
[3]*CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France*

(Presented 9 May 2012; received 6 May 2012; accepted 8 June 2012; published online 21 August 2012)

With installation of the ITER-like wall in JET a major diagnostic upgrade to measure the neutral gas pressure and composition in the sub-divertor region has been completed, to characterise retention and outgassing of the new metallic first wall. The upgrade includes two new magnetically shielded systems consisting of sensitive capacitance manometers and residual gas analysers, both capable of providing data during plasma operation. These enable absolute pressure and gas composition measurements (pressure range: 10^{-5}–10^{-1} mbar, mass range: 1–200 amu, respectively) and have been used to characterise the neutral gas behaviour under various plasma conditions. [http://dx.doi.org/10.1063/1.4732175]

I. INTRODUCTION

The global particle balance in present nuclear fusion experiments, such as the largest existing tokamak JET, represents not only a key for a better understanding of the plasma density behavior and control but is also a measure for the removal efficiency of impurities from the vacuum vessel. These impurities are either deliberately injected into the fusion plasma (e.g., during nitrogen seeding experiments to control the plasma wall interaction processes, massive gas injections of noble gases as a last resort to protect the plasma facing components from damage following disruptions), or are produced in the plasma itself (such as the helium ash resulting from successful deuterium-tritium (D-T) fusion reactions). The latter will be essential for future nuclear fusion reactors, which will be based on the (D-T) fusion process. To measure the global particle balance, the injected amount of gas and the amount pumped by the pumping system have to be assessed to finally deduce the retained quantity in the vacuum vessel.[1] While the injection systems at JET are well characterised and the precise flow of injected gas is known at all times, the gas pressure evolution in the vacuum volume as the result of the gas injection has to be measured *in situ* with the help of pressure gauges to deduce the pumped gas quantity. Both the absolute pressure and the gas composition, which can strongly vary during deliberate gas impurity injections, are necessary to deduce retention in the first wall. In particular with the new ITER-like metal wall[2] in JET and the expected lower retention compared to a carbon wall,[3] an improved accuracy of the pressure measurements had to be achieved. For this purpose, new absolute pressure gauges have been installed in the sub-divertor region, in addition to the standard Penning pressure gauges at JET. Furthermore, residual gas analysers (RGA) have been added to the routinely working gas-composition analysis based on Penning gauge spectroscopy.[4,5] Both the new absolute pressure gauge sub-system and the RGA sub-system are equipped with magnetic shielding and have been designed to provide accurate data throughout the plasma pulse. These new systems were brought into routine operation in 2011 with the beginning of operations with the new ITER-like wall in JET, and have been used for the characterisation of retention, gas composition under various divertor plasma conditions and the outgassing after the pulse.

II. EXPERIMENTAL ARRANGEMENT

A schematic of the current layout of the JET sub-divertor gas analysis system can be seen in Fig. 1. The original setup and performance has been described in detail by Hillis.[4]

The upgrade of the diagnostic, utilising two new sub-systems and their location with respect to the vacuum chamber, is indicated in Fig. 1 (grey squares).

The first sub-system, the *Absolute Pressure Measurement*, consists of two capacitance manometers (*MKS* Baratron) which provide absolute and gas independent pressure measurements in the range of 10^{-5}–10^{-1} mbar with a time constant of ∼100 ms. These gauges are equipped with a soft iron magnetic shielding, as shown in Fig. 2(a), to screen the gauges from magnetic fields during plasma operation in the order of 100 mT (inside shielding 0.6 mT in worst case scenario). The magnetic shielding is designed to allow simple maintenance of highly contaminated (tritium and beryllium) vacuum components, with the aid of containment systems commonly used at JET. In Fig. 2(b), one side shielding is removed to easily access the gauge for replacement with the aid of such containment systems. As the installed gauges are very sensitive to mechanical vibrations, which can be particularly high during disruptions, measures have been taken to ensure

[a)]Contributed paper, published as part of the Proceedings of the 19th Topical Conference on High-Temperature Plasma Diagnostics, Monterey, California, May 2012.

[b)]Author to whom correspondence should be addressed. Electronic mail: uron.kruezi@ccfe.ac.uk.

[c)]See the appendix of F. Romanelli, *et al.*, Proceedings of the 23rd IAEA FEC 2010, Daejeon, Korea.

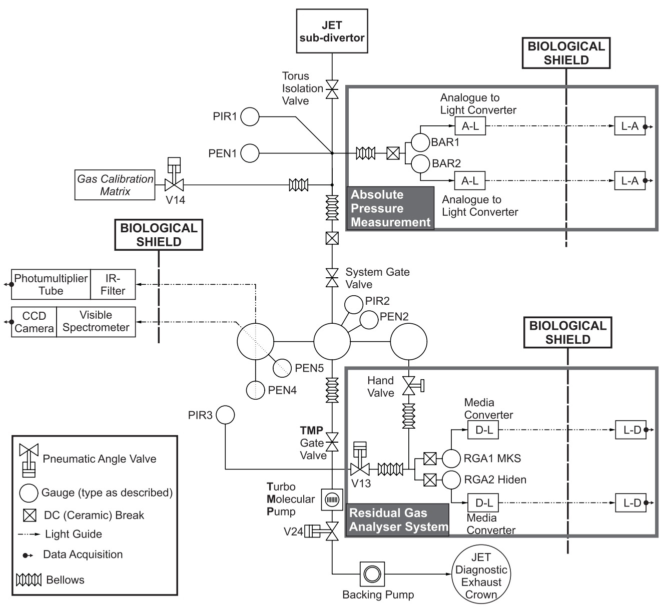

FIG. 1. Scheme of neutral gas analysis diagnostic at JET (Gauge acronyms: PENx: Penning gauge x, PIRx: Pirani gauge x, BARx: *MKS* Baratron x).

vibration decoupling (edge welded bellows) and damping (braided bellows and vertical and horizontal silicon dampers). The latter is shown in Fig. 2(c). These silicon dampers in parallel with ceramic vacuum breaks are additionally used to electrically isolate the gauges from the vacuum vessel and the support structure to avoid grounding loops and thereby reduce the electromagnetic noise typically present at JET.

The analogue signals provided by the gauges are transferred behind the biological shield with the help of optical fibres and analogue-to-light converters (*A.A. Lab Systems Ltd.* AFL-300). Together, these measures enable measurements of pressures as low as 10^{-5} mbar with a minimum detection level given by the gauge noise level (standard deviation in case of vacuum pressures below 10^{-7} mbar) in the range of approximately 0.7 mV, corresponding to 7×10^{-6} mbar. To minimise the influence of signal offset drifts due to temperature changes, an automatic offset correction is applied to the acquired pressure data before each plasma pulse (typical pressures $< 10^{-7}$ mbar). The data provided by the baratrons is used to cross-calibrate existing Penning discharge gauges,[4] to improve the accuracy of low pressure measurements (down to 10^{-8} mbar) and the routinely working gas-composition analysis based on Penning gauge spectroscopy.[5] This existing gas composition measurement can now be cross compared with

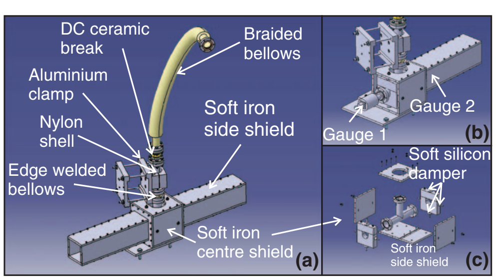

FIG. 2. (a) Setup of the absolute pressure measurement. (b) Soft iron side shield removed for easy access to the gauge. (c) Disassembled soft iron centre shield with horizontal and vertical soft silicon vibration dampers.

an available independent method, the *Residual Gas Analyser System,* which is the newly installed second sub-system (see Fig. 1). It consists of two magnetically shielded RGAs, one overview (m/e = 1–200 amu *HIDEN*) and one high resolution (m/e = 1–6 amu *MKS*) RGA. The latter provides a resolution of ∼0.01 amu; hence it can distinguish between molecular deuterium and helium, which is required to characterise fuel removal, cleaning and isotope exchange. To enable stable operation under high sub-divertor pressures, the RGA system can be differentially pumped (pressure reduction up to 1:1000). To reduce the negative influence of tritium contamination on the RGA performance, the RGA analyser is actively heated at about 90 °C for continuous operation (and up to 200 °C for short term bake out). The RGA system, similar to the absolute pressure measurement system, is mounted electrically isolated with one dedicated grounding point. All control and measurement signals are transferred by means of optical Fast Ethernet.

III. APPLICATION OF THE ABSOLUTE PRESSURE GAUGES AND RESIDUAL GAS ANALYSERS

In Fig. 3 the main parameters for intershot gas balance measurements are shown for a normal JET plasma pulse (#80907 – L-H transition studies). As a consequence of the known gas fueling rate (Γ_{FUEL}) the plasma density, represented by the line integrated central density (b), increases. During the limiter phase a small recycling flux in the outer divertor region can be observed (c), which significantly changes in the divertor phase. During this phase most of the interaction of the plasma with the plasma-facing components appears in the divertor. A significant quantity (∼75%) of the recycled particles are pumped by the sub-divertor cryogenic pump. The resulting pressure (d) in front of the pump can then be measured by Penning gauges (*Pfeiffer* IKR 60) and the newly installed baratrons (d), whereas the gas composition (e) can be observed with Penning gauge spectroscopy and the new RGAs.

During a typical plasma pulse the pressures in the sub-divertor vary in the range of 10^{-5} mbar or less and up to 10^{-3} mbar in the divertor phase. The pressure signal provided by the baratron is linear and gas independent (absolute pressure) throughout the entire measurement range, whereas the pressure measured with a Penning gauge strongly depends on the gas composition (partial pressure) and the absolute ambient pressure. Above an ambient pressure of 10^{-4} mbar Penning gauges tend to operate in a nonlinear manner. As the signal measured with a Penning gauge additionally depends on the history of the gauge (life time, operating conditions, etc.), regular calibrations are essential to provide high quality pressure measurements. The baratron is able to provide calibration data, especially in the nonlinear operation region 10^{-5} mbar to 5×10^{-3} mbar (max. operational Penning gauge pressure). Penning 1 and Penning 2 in Fig. 3(a) were calibrated during dedicated deuterium gas pulses without plasma operation. A significant deviation of these signals from each other during plasma pulses might be used to easily distinguish the presence of a gas composition other than the one used for cross-calibration. Penning 2 is in good agreement with the baratron

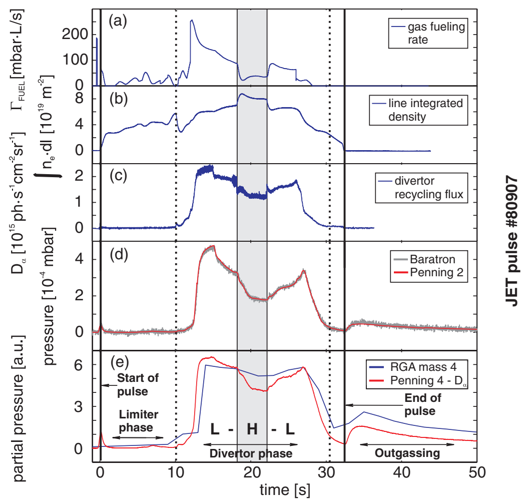

FIG. 3. Main parameters for intershot gas balance measurements during JET plasma pulse # 80907 are (a) the gas fueling rate, (b) the line integrated density, (c) the divertor recycling flux, (d) the pressure measurement in the sub-divertor region, and (e) the gas composition measurement (comparison between the D_α signal measured with Penning gauge spectroscopy and mass 4 measured with the new *HIDEN* RGA are shown).

measurement during the shown plasma pulse, with only deuterium present in the plasma. Penning 1 on the other hand does differ significantly, which is related to the magnetic field experienced by this particular gauge during the plasma pulse. It is located closer to the vertical magnetic field coils; therefore, the magnetic field can be significantly stronger (100–200 mT). These results demonstrate that it is not an entirely valid assumption that on Tokamaks this widely used gauge type is insensitive to magnetic fields. In fact, various Penning pressure measurements at JET indicate a significant influence of the magnetic field during different plasma conditions. No significant influence on the baratron and the RGAs can be observed which confirms the screening efficiency of the magnetic shielding.

In Fig. 3(e), a cross comparison of the spectroscopically measured Balmer D_α signal, which is linear to the deuterium partial pressure up to 3×10^{-2} mbar,[4] and the temporal signal of mass 4 measured with the RGA (time resolution of 2 s) is shown. Both signals are not calibrated with respect to the partial pressure but generally follow the trend of the pressure signal measured by the baratron. The mass signal acquired with the RGA is in good agreement with the Balmer D_α signal originating from the Penning discharge in Penning 4. The differences in the signals are mainly caused by the different time constants of both systems and the relatively slow time resolution of the RGA. Before and after a plasma pulse a continuous profile mass scan in the range of 1–100 amu (resolution: 0.1 amu, cycle duration: 100 s) is performed. During the pulse a cycle of 19 selected mass scans in the range of 1–44 amu, with a duration of 2 s, is used. The new absolute pressure measurement and the new RGA has been operational since the beginning of the ITER-like wall experiments and has provided valuable data for a wide range of experiments.

With accurately measured pressures in the range of 10^{-5} mbar to 10^{-3} mbar, retention measurements could be improved[4] and measurements of the dynamical retention during plasma pulses are possible for the first time.[6] Throughout high density plasma pulses with sub-divertor pressures in the order of 10^{-2} mbar,[7] as well as in massive gas experiments[8] with pressures up to 3×10^{-2} mbar, continuous measurements were possible; the relatively high pressure environment has exceeded the operational range of all other standard JET vacuum vessel pressure gauges.

The RGA system has been used in parallel to study wall conditioning,[9] outgassing during the limiter, divertor and post pulse phase in general, and in particular ammonia formation in nitrogen seeding experiments.[10]

IV. SUMMARY

Accurate pressure and gas composition measurements in the sub-divertor of JET and the new ITER-like wall project are essential for a better understanding of retention and removal of fuel and impurities from the vacuum vessel. For this purpose, a major upgrade of the sub-divertor gas analysis system has been undertaken. In addition to the existing Penning gauge pressure measurement and the routinely working gas-composition analysis based on Penning gauge spectroscopy, two baratron absolute pressure gauges (pressure range: 10^{-5}–10^{-1} mbar, time constant: ∼100 ms) and two residual gas analysers have been installed. The residual gas analysers are capable of providing mass spectra in the range of 1–200 amu and are typically running on 19 selected masses in the range of 1–44 amu with a time resolution of 2 s during a plasma pulse. Both new systems are additionally used to cross-calibrate existing Penning-gauge-based pressure and gas composition measurements. These new gauges and RGAs, equipped with soft iron magnetic shielding, enable undisturbed and reliable measurements during plasma operation and have been used during the experimental JET campaigns in 2011 and 2012 for the characterisation of retention, outgassing and the gas composition under various plasma conditions.

ACKNOWLEDGMENTS

This work, supported by the European Communities under the contract of Association between EURATOM/FZJ, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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