Concepts for Improving the Accuracy of Gas Balance Measurement at ASDEX Upgrade

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The ITER fusion reactor which is under construction will use a deuterium-tritium gas mixture for operation. A fraction of this fusion fuel remains inside of the machine due to various mechanisms. The evaluation of this retention in present fusion experiments is of crucial importance to estimate the expected tritium inventory in ITER which shall be limited due to safety considerations. At ASDEX Upgrade (AUG) sufficiently time-resolved measurements should take place to extrapolate from current 10 sec. discharges to the at least intended 400 sec. ones of ITER. To achieve this, a new measurement system has been designed that enables accuracy of better than one per cent.

1. Introduction

ITER is going to use an equal mix of deuterium and tritium for operation. Fraction of this fusion fuel remains inside the machine due to various mechanisms like implantation and co-deposition. The proportion depends mostly on the wall materials and ranges between some 0.1% in metal machines and up to 30% in carbon machines [1]. From licensing restrictions the limit for the inventory of releasable tritium in the vacuum vessel is 700g [2]. The measurement of deuterium retention in present devices is crucial for the development of operational scenarios of ITER.

2. Gas balance

The gas balance is based on the precise measurement of the injected and pumped particles in and from the vacuum vessel during the plasma discharge and/or between plasma discharges for quantifying the retained amount of particles inside the vessel.

$$D_{Retained} = D_{Inserted} - D_{Removed}$$

Therefore all gas sources as well as the gas sinks have to be examined carefully.

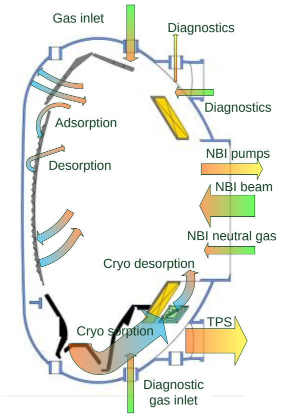

Figure 1: Overview of gas flows in AUG.

Pumping speed S [m^3/s] for different gas sinks [3].
Pressure range:
1e-3 Pa < p < 1 Pa:

Torus Pumping System (TPS):
$S=16.1-6.131 \cdot p+1.835 \cdot p^2$

Cryo pump:
$S=115 + 276.6 \cdot p$

Neutral Beam Injection (NBI):
$S=53.01 + 77.68 \cdot p$

Diagnostics:
$S<0.5$

Figure 1 gives a simplified overview of the gas flows in (green), within (red) and out (yellow) from the vacuum vessel. The different types and areas of retention are symbolized in blue colour. The cryo pump in the lower divertor region is the main gas sink however warming up leads to a controlled release of gases retained by cryosorption. These gases subsequently are pumped by the gas transfer pumps of the TPS out of the vessel.
The NBI acting as source and sink is quite complex and should therefore not be used during gas balance measurement.
The Gas Inlet System is the main gas source and consists of 20 fast gas valves of the General Atomic type. These valves are calibrated due to a PVT calibration at stable temperature conditions into the vacuum vessel. Thereby the pressure rise is measured with a high accuracy Baratron (<0.1% measurement error). The torus volume is known with an accuracy of ≈0.1%, thus an overall measurement accuracy of these gas flows of less than 1% is expected.

3. Challenges of retention measurement

The different phases of retention (Figure 2) can be classified in the segments: Plasma density build up (green); wall saturation (yellow); steady state phase (blue) and plasma ramp down (red) [1].

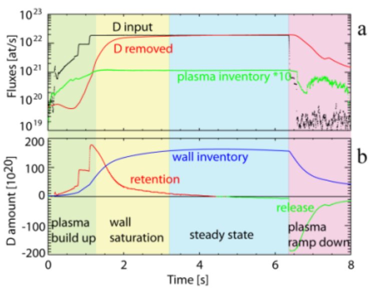

Figure 2: Phases of wall retention. a) Shows D input and removal. b) Fluxes to the PFCs and the wall inventory [1].

After the discharge still a considerable amount of gas is removed over a period of many minutes at a very low pressure.
According to the Ideal Gas Law the amount of gas is determined by its volume, pressure and temperature.

$$n = (P \cdot V) / (R \cdot T)$$

Whereas the measurement of pressure and volume also within a complex vacuum chamber as that of AUG is possible with a high precision of less than one per cent in special circumstances the accuracy of a gas temperature measurement is always limited.
This is largely because inside the vessel the temperatures ranging between a few (cryo pump) and several hundred Kelvin (limiter), as shown in Figure 3.

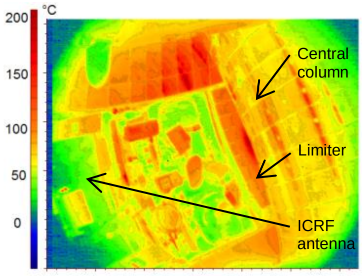

Figure 3: Thermography of in vessel components.

Therefore, established measurement methods that use the known pumping speed of the installed vacuum system as well as static techniques that collect all the gas inside the vacuum vessel by closing all the vessel valves during and after the discharge [4] are afflicted with this measuring fault.
To overcome the problem of inhomogeneous temperature distribution inside, a measurement outside the vacuum vessel is preferable. To improve the accuracy therefore the gas should be enclosed in a volume to create stable conditions. The necessary size of this volume depends on the amount of gas and the storage pressure. At atmospheric conditions this is about 100 litres for one operational day. Accordingly a storage pressure of 1000 Pa – that would be an advantage for explosion prevention – requires a volume of 10000 litres. From operability point of view an accurate gas measurement is therefore best at atmospheric pressure because of the space limitations in the experimental hall.
Two possibilities are conceivable principally:
Storage of gas in a repository with constant volume by raising pressure: On the first view this method looks quite simple. The components, a calibrated container of sufficient size and a high accuracy pressure gauge, are commercially available. The difficulties are more at the operational side. For the compression of the gas into the container it is necessary that the compression ratio is more or less independent from the pressure inside. Furthermore a steady compression leads to an additional heating of the gas. As the pressure varies within a wider range the reading of the pressure gauge has a higher measuring fault.
Storage of gas in a repository varying the volume at a constant pressure: Thereby the retroactivity to a supply system is kept as low as possible and on the other hand temperature as well as pressure measurement could be done with best accuracy.

4. Situation at AUG

To fulfil the operational requirements on final pressure and pumping speed the pumping system (TPS) consists of three stages (Figure 4). The high vacuum (HV) part comprises 11 turbo molecular pumps (TMP) (Pfeiffer TPU2301) connected to the vacuum vessel with a tubing of approximately 6 metre of length. Gate valves are installed to shut off single pumps. All TMPs are connected with an angle valve to the common fore vacuum line. This is pumped by two similar fore vacuum pumping units (FV) consisting of a roots pump and two parallel rotary vane pumps (Edwards E2M275) and rotary piston pumps (Oerlikon Leybold DK200) respectively.
In normal operation only one FV-set is necessary. During pumping down or for a very high quantity of gas the redundant one is used additionally.

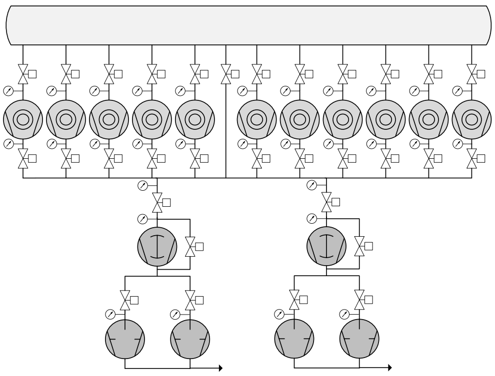

Figure 4: AUG Vacuum system (TPS)

The typical operation with plasma discharges and subsequent regeneration of cryo pump leads to a pulsed pressure profile shown in Figure 5.

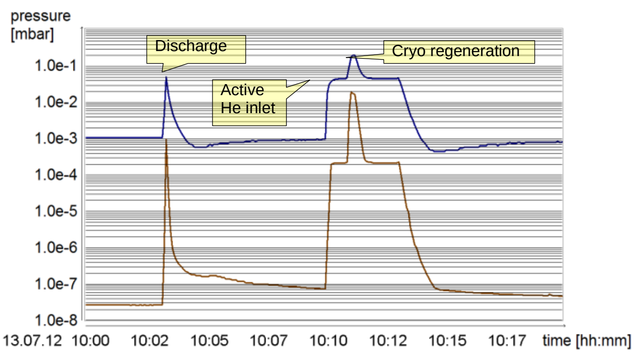

Figure 5: Pressure profile of TMP HV-side (brown) and FV-side (blue) during plasma discharge and cryo regeneration.

A gas measurement at the atmospheric end of the compression is influenced also by the pumps and vacuum components installed.
The leak rate of components in the high vacuum part of the TPS is very low (see Table 1) and therefore negligible, whereas especially due to the leak rate of the roots,

rotary vane and piston pumps about 3 Pa m^3 air are running in the system within 1000 s (time between 2 discharges) leading to an error of more than 3% (related to a gas amount of 100 Pa m^3/s).

Table 1: Leak rates of installed vacuum components.

Component	Leak rate [Pa m^3/s]	Pumping speed [m^3/s]
HV tubing	< 1e-10	-
Gate valve	< 1e-10	-
TMP	< 1e-10	11 · 2
Angle valve	≈ 1e-8	-
FV Tubing	≈ 1e-8	-
Roots pump	≈ 1e-3	2 · 2
Rotary vane pump / Rotary piston pump	≈ 1e-3	2 · 2 · 0.075

An additional uncertainty comes from the required pump oil. The solubility of gases in oil is up to 0.5% vol. With the amount of oil in one pump (28 l) this results in an error of up to 14% with respect to the gas amount of one discharge.
Hence the influence of the leak rate is essential for achievable accuracy of measurement, the existing FV-units are not sufficient for the desired accuracy. On the other hand there was the request for an oil-free FV-system to reduce hydrocarbons in the vacuum vessel.

5. Hermetic and dry fore vacuum system

The weaknesses of the current FV system could be overcome by using a new designed pumping unit. After an investigation of commercially available pumps with various operating principles a design for a replacement FV-unit has been planned and the functional efficiency could be confirmed with the assistance of experts from a major vacuum company.
An additional assessment is currently underway to give a second proof of concept and find an alternative one respectively.

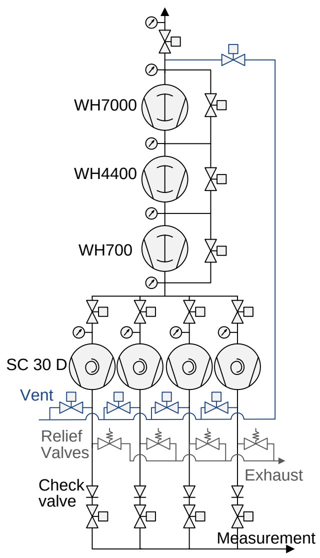

Figure 6: Four stage dry and hermetic pumping unit.

The design of the new FV-unit (Figure 6) is planned with four pumping stages. First 3 stages are consisting of hermetically sealed roots pumps (Leybold WH series) without rotary shaft seals. Thus enables an external leak rate of less than 1e-6 Pa m^3/s whereas each stage provides a compression of about factor of 10.
The final compression to atmosphere is done by a parallel installation of 4 absolutely oil-free operating scroll pumps (Leybold SC30D). Although the construction principle of these pumps is not really hermetic, their long term external leak rate is about 1e-7 Pa m^3/s due to a combination of gasket and hardened shaft.

This set-up overcomes the general problem of dry pumps regarding the compression limitation during pumping light gases without an additional purging.
The expected performance values in respect of attainable final pressure (<1e-1 Pa) and pumping speed (≈2 m^3/s) are quite similar to the existing FV-unit however, the overall leak rate is about 3e-6 Pa m^3/s and hence a factor of 1000 lower (0.003% related to 1000 s).
Laboratory studies with a comparable but smaller scroll pump (Varian SH100) in combination with a drum-type gas meter (Ritter TG05) were carried out. Thereby the fundamental suitability of the combination of dry type pump and a volumetric gas meter could be demonstrated. However, they showed the need for some additional equipment for making it reliable and operational. Scroll pumps stop almost immediately in the event of failure and vent themselves from the exhaust side. To prevent this, an independently working non-return valve is envisaged. To avoid mechanical damage in the case of malfunction of the gas measurement system each scroll pump is equipped with a pressure relief valve on the exhaust side. An isolating valve on both the vacuum and the exhaust side is installed for disconnecting single scroll pumps in case of breakdown or maintenance and variation of pumping speed purposes.
Two difficulties have been shown at the operation of this system: For light gases as helium (He), deuterium (D_2) and especially hydrogen (H_2) the attainable compression of the scroll pump alone is lower than specified because of the higher backflow. Therefore the final pressure of the scroll pump is only in the range of a few hundred Pa and the vane heats up more than usual.
These tests demonstrated that the drum-type gas meter does not represent a suitable solution for this application, due to the large measurement uncertainty it exhibits in the pulsed gas flow regime, typical of tokamak operation
The estimated costs are in the range of Euro 100 to 150 thousand but are partially necessary to be expended anyway to maintain and improve operating reliability of the current vacuum system.

6. High precision gas measurement

A high precision measurement independent from gas species is preferably a direct method. There are two common make-ups:
A bell prover (Figure 7a) consists of a vertical tank filled with a liquid serving as a seal. An inverted tank (the bell) is counterweighted placed inside the lower tank to ensure a constant excess pressure of a few hundred Pascal. Inside the bell the gas quickly adopts a steady-state.
An actively driven piston prover (Figure 7b) is sealed with gaskets to overcome the need of a liquid sealing. It may be tempered for even higher accuracy.
The attainable accuracy of both devices is comparable and yields about 0.2%. It is mainly given by the errors of measurement of volume (<0.1%), temperature (<0.03%) and pressure (<0.1%). Other uncertainties like gas storage in sealing liquid or gasket and surface effects are usually very low [5].

The gas measuring bell as well as the piston prover represents an advanced primary standard used by national authorities for metrology like PTB.

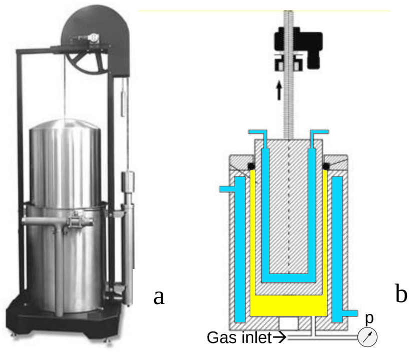

Figure 7: Picture of a bell prover a) and scheme of water tempered (blue) piston prover b).

Currently discussions are underway with experts from PTB and manufacturers of bell prover and piston prover to clear several uncertainties relating interfaces and design parameter.
The costs are estimated roughly to Euro 250 thousand for an aligned bell or piston prover and Euro 100 thousand for necessary adaptions and modifications for operability with the pumping system.

7. Layout and operation of the system

The measurement system (Figure 8) is operated with only a minor mutual interference to the pumping system. Via the open valve V1 (V2/V3 closed) all pumped gas is stored in the bell prover. A check valve prevents from unintentional back flow at a loss of overpressure from the pumps.

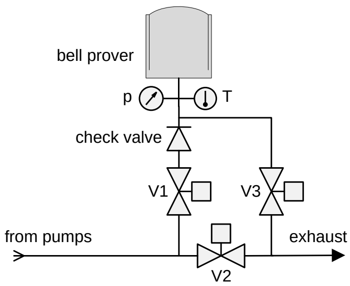

Figure 8: Measurement system with operational valves

Reading of P, T and the change of volume gives the amount of gas at any time. Via the open V2 (V1/V3 closed) gas can be bypassed if necessary whereat the gas amount in the prover be sustained. The bell is emptied via the open V3 to the exhaust.
The accuracy of the system according to section 6 is determined by the errors of the bell volume, the pressure gauge and the temperature sensor. Therefore the total attainable precision should be better than 0.2%.
The length of the tubing of the TPS, the amount of pumping stages and the tubing to the measurement system are limiting the expected temporal resolution to a few seconds.
Highly time resolved measurements were done presently by numerically integrating the gas removed from the torus. Therefore the pumping speed of the TPS as a function of pressure was calibrated in situ to consider various conductances empirically [3]. High accuracy Bayard-Alpert pressure gauges (1e-1 Pa < p < 1e-5 Pa) and calibrated capacitance manometers (10 Pa < p < 1e-3 Pa) are used to encompass the entire pressure range. To take into account variations of gas composition the B-A gauge is calibrated against the capacitive gauge at the end of each discharge. This approach enables a time resolution in the sub-second range.
The accuracy of this time resolved measurement can be significantly improved by normalizing its integral over the time to the total amount of gas measured by means of the bell prover after one plasma discharge.
For precise time resolved measurements on gas retention, the cyro pump has to be switched off, but it is expected that with some operating experience a good estimation is also possible while the cryo pump is running.
According to the results of studies conducted all desired operational scenarios can be handled and the objectives are fulfilled with this make-up.

8. Summary

A concept design has been developed for improving the accuracy of gas balance measurement at AUG. To reach the requirements for exactness of 1% or better a system outside the vacuum vessel is planned. Therefore a new hermetic fore vacuum system with a sufficiently low leak rate is intended and a concept already proved.
According to the previous investigations the new system is functionally with all operating conditions of AUG. The proposed requirements are expected to be fulfilled completely.
The estimated accuracy of measurement of the gas amount pumped out is in the range of 0.2%. This is considerably below the measurement precision of the gas inlet. Hence an overall accuracy for gas balance measurement in the range of less than 1% is expected.
The clear separation between vacuum generation and gas compression to atmosphere pressure respectively and the measurement system itself is seen as a big advantage at both construction (and financing) and operation.

References

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