# Calibration of the neutral gas systems of Wendelstein 7-X

G. Schlisio,[1,*] H. Viebke,[1] T. Bräuer,[1] D. Naujoks,[1] O. Volzke,[1] V. Rohde,[2] B. Jagielski,[1] T. Kreyemer,[1] P. McNeely,[1] PRELIMINARY AUTHOR LIST,[1],[1],[1],[1],[1],[1],[1] and the W7-X team[b]

[1]*Max-Planck-Institut für Plasmaphysik, Wendelsteinstraße 1, 17491 Greifswald, Germany*

[2]*Max-Planck-Institut für Plasmaphysik, Boltzmannstraße 1, Garching, Germany*

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[b] See author list of T. Klinger et al., Nuclear Fusion 59 (2019) 112004

## Abstract

Fusion plasmas heavily rely on the surrounding neutral reservoir for fueling and exhaust, hence precise knowledge of it is basis for many detailed diagnostic and physics investigations. The observed pressures range from UHV (O(1e-6 Pa)) surrounding the main plasma to medium vacuum (O(1 Pa)) in the plasma-compressed exhaust stream, so a wide range of precise measurement is required.

We present the calibration effort of all neutral-reservoir related systems, such as gauges, valves, and pumps, with respect to their relevant quantities: The pumping system, consisting of turbomolecular pumps and cryo vacuum pumps, was characterized for pumping speed. The gas injection systems were characterized for gas injection rates. The pressure measurement systems were calibrated to a common standard. The plasma vessel volume was determined. The NBI box volume and internal getter pump pumping speed were determined.


## I. INTRODUCTION

The optimized modular stellarator Wendelstein 7-X (W7X) recently went into operation with a water-cooled divertor [reference]. With the change from the previously utilized inertially cooled divertor [reference] the components in the plasma vessel (PV) changed dramatically, amongst other things a cryo vacuum pump (CVP) was installed in the subdivertor space [reference?].

This changed the effective volume available for gas to expand into from the previously estimated value

The following sections are organized as follows: First, we

## II. VACUUM SYSTEM OF W7X

The Plasma Vessel (PV) of W7X is equipped with 30 turbo-molecular pumps (TMPs), individually separatable from the PV by a gate valve. These 30 TMPs are located in receded positions to safeguard from magnetic field, and a evenly distributed around the machine. For details refer to [1].

Additionally, starting from OP2.1, the low iota sub-divertor space is equipped with a cryo vacuum pump (CVP). Details on this device can be found in [reference]. The CVPs cannot be


* georg.schlisio@ipp.mpg.de

decoupled from the PV and can only controlled by their temperature determined by the circulated fluid temperature.

The neutral beam injection system (NBI) consists of two identical boxes (NI20, NI21), equipped with a large Titanium getter pump and a smaller TMP. Each box is separated from the PV with a large gate valve.

## III. PRESSURE MEASUREMENT

The torus pressure is observed by various systems serving different purposes.

The main operational pressure monitoring consists of combinations of commercial Penning (cold cathode) and Pirani (conductance) gauges observing the pressure over the full range at low time resolution (1 Hz). This system is operational throughout the entire campaign and collects total pressures pre-calibrated for N2. The measurement positions are close to the TMPs in a low-magnetic-field area.

It is supplemented with two sets of capacitance manometers with overlapping range, providing gas-type-independent measurement of pressure in the high and medium pressure range. These are also sampled at 1 Hz time-resolution and are mounted in similar locations as the main operational pressure monitoring.

For further precise measurement at pressures from 1e-4 Pa to 10 Pa an additional capacitance manometer with a full range of 0.1 Torr has been installed and outfitted with an automated zeroing system. This serves as total pressure reference for calibration of all other systems. For observation of fast pressure changes in different positions inside the vessel, two systems exist: The crystal cathode pressure gauges (CCPG) are hot cathode gauges adapted for use in high magnetic field [2, 3] and measure in up to 18 positions inside the PV. They are sampled with minimum 1 kHz and provide gas-type-dependent ion currents, which have to be calibrated to be interpreted as total pressure.

There also exist WISP gauges (Wisconsin In-Situ-Penning) [4], which are spectroscopically enhanced cold cathode gauges capable of measuring gas-type dependent total pressure as well as, with help of the observed line intensities, partial pressures – typically for He and H2. An overview of all described systems can be found in figure 1 with additional details in table I.

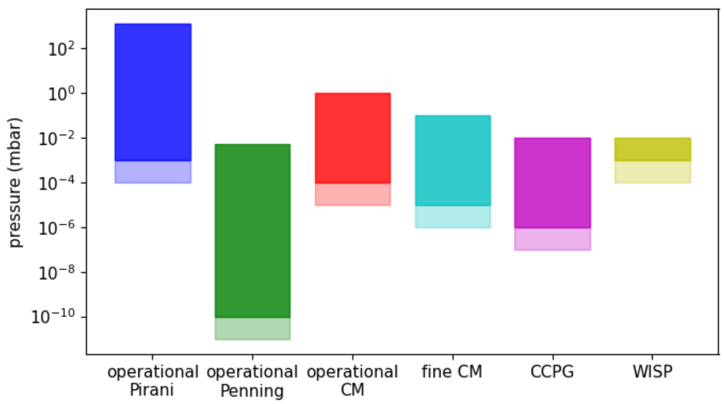


FIG. 1. Overview of the gauge systems available on W7-X. For more details see table I. (color online)

| System | sensor type | range (mbar) | sampling rate (Hz) | toroidal coverage | distance from PV | reference |
|---|---|---|---|---|---|---|
| op. Pirani | Pfeiffer RPT100 | $1 \cdot 10^{-3} \ldots 1200$ | 1 | full | 4 m | - |
| op. Penning | Pfeiffer IKR070 | $1 \cdot 10^{-11} \ldots 5 \cdot 10^{-3}$ | 1 | full | 4 m | - |
| op. CM | MKS Baratron | $1 \cdot 10^{-5} \ldots 100$ | 1 | 2 pos. | 5 m | - |
| fine CM | MKS Baratron AA06 0.1 | $1 \cdot 10^{-6} \ldots 1 \cdot 10^{-1}$ | 3 | 1 pos. | 5 m | - |
| CCPG | hot cathode ionization gauge | $1 \cdot 10^{-7} \ldots 1 \cdot 10^{-2}$ | 1000/2000 | 18 pos. | in-vessel | [3] |
| WISP | in-situ Penning | $1 \cdot 10^{-4} \ldots 1 \cdot 10^{-2}$ | 1000 | 3 pos. | in-vessel | [4] |

TABLE I. Details of the available pressure gauge systems at W7-X.

## IV. GAS INLET SYSTEMS

There are a number of plasma fueling systems: The main gas valves are toroidally symmetric on the inboard midplane of the torus. The divertor gas inlet system [reference] is located in each of the 10 divertor modules in the low iota section of the divertor. The steady-state pellet injector (SSPI) [reference] Additionally, there are a few diagnostics puffing small amounts of gases for technical or diagnostic purposes: The gas-puff imaging (GPI) diagnostics injects small amounts of super-sonic H2 and He into the PV [reference]. The ion-cyclotron-resonance-heating (ICRH) antenna is equipped with a gas inlet system to facilitate favourable coupling conditions in front of the antenna [reference]. The endoscopes [reference] use H2 venting of their optical components and inject upto XX mbarl/s into the vessel. The neutral beam injection system (NBI) [reference] also acts a particle source, by both the beam and parasitic gas injection from other sources, e.g.

dragged-on neutralizer gas and beam duct outgassing.

## V. CALIBRATED PRESSURE STANDARD

An externally calibrated pressure standard (MKS Baratron AA06 0.1Torr) was used as a reference to calibrate the operational gauges. To counter inevitable sensor drift an automatic zeroing was applied daily, if the observed pressure in the Penning system was below $1 \cdot 10^{-7}$ mbar.

## VI. VESSEL VOLUME DETERMINATION

The PV volume was determined with two independent methods, first a gas expansion from a well-known volume ("expansion method") and second a well-defined gas inlet ("injection method"). Both methods were conducted with the TMP gate valves closed and the CVP warmed up, to ensure no pumping on the plasma vessel. Uncertainty propagation was performed for each single measurement, all results are combined in a weighted average for a final value. With the individual measurement results $v_i$ and their corresponding uncertainties $\delta_i$ the final value $V$ with uncertainty $\Delta$ is given by

$$\Delta^2 = \left( \sum_i \frac{1}{\delta_i} \right)^{-1} \tag{1}$$

$$V = \Delta^2 \sum_i \frac{v_i}{\delta_i}. \tag{2}$$

The result of each measurement and the weighted average are given in table VI B

### A. Expansion method

From the ideal gas law we get the volume $V$ with the pressure difference $p$ and the injected gas amount $nk_bT$:

$$V = \frac{nk_bT}{p}. \tag{3}$$

A well characterized test volume with 0.392 116 L was filled with Argon gas up to a pressure of 0 mbar and left for temperature equilibration. Subsequently the test volume, attached to the DRGA diagnostic [5], was expanded into the diagnostic and, through the open gate valve, into the PV, where the resulting pressure was observed with a capacitance manometer.

| method | W7-X program | Gas type | volume (l) | uncertainty (l) |
|---|---|---|---|---|
| expansion | - | Ar | 116 842 | 1 076 |
| injection | DCH_20230414-event2 | N2 | 109 672 | 2 036 |
| injection | DCH_20230414-event3 | N2 | 107 780 | 167 |
| injection | DCH_20230414-event4 | N2 | 107 786 | 251 |
| injection | DCH_20230419-event1 | He | 110 697 | 319 |
| injection | DCH_20230419-event2 | H2 | 107 307 | 132 |
| injection total | | | 107 795 | 92 |
| Grand total | | | | |

TABLE II.

For the expansion method, a well characterized test volume of was filled with Nitrogen gas up to a pressure of 1000 Pa and subsequently expanded into the vessel.

### B. Injection method

For the injection method, a mass flow controller (MFC, MKS GE50A) with a fullscale of 5000 sccm was used at an injection rate of 9 $\mathrm{mbar\,L\,s^{-1}}$ for 120 s, resulting in a pressure increase of about 1 Pa. The PV volume is then calculated by

$$v = Q \cdot \frac{T}{p} \tag{4}$$

with the injection rate Q, injection time T and pressure difference p. The measured pressure was corrected for the leak rate, which was assumed to be linear and measured to be 2.8 $\mathrm{mbar\,s^{-1}}$.

## VII. NEUTRAL GAS MANOMETERS AND WISP GAUGES

Pressure steps to compare against known reference gauges, conducted with and without magnetic field for He, H2 and – for the WISP gauges – in gas mixtures with 5%, 10%, 20%, and 50% He in H2. The obtained data was averaged over the plateau time of 10 s and individually fitted for each gauge with the orthogonal distance regression algorithm [reference https://doi.org/10.6028/nist.ir.89-4197] to obtain a model for conversion from raw ion current to absolute pressure.

## VIII. NBI BOX VOLUME AND PUMPING SPEED

The W7X NBI consists of two practically identical systems, NI20 and NI21, [reference] which feature a large UHV volume with included Titanium getter pump. The box volume was determined in an expansion experiment, where the PV was filled with He up to a pressure of $9.7621 \cdot 10^{-3}$ mbar and subsequently expanded into the NI20 system by opening the gate valve. After equilibration, a pressure of $7.7213 \cdot 10^{-3}$ mbar was measured, yielding an NBI box volume $V_{NBI} = 0.2643 * V_{PV} = 28.4910\,\mathrm{m}^3$. The getter pump pumping speed was determined with a similar experiment, but with Hydrogen instead of Helium. The pressure drop after opening the gate valve was fitted with

$$p(t) = p_0 e^{-\frac{S}{V} \cdot t} + p_{base} \tag{5}$$

Where $p_0$ is the initial pressure, S the pumping speed, V the total volume of the system, and $p_{base}$ the observed base pressure after equilibration.

## IX. TMP PUMPING SPEED

The TMP pumping speed was determined by a number of gas injection experiments...

## X. CVP PUMPING SPEED

The CVP pumping speed was determined by a number of experiments for a set of gases: H2, He, N2, Ar, both with and without TMP.

## XI. QRT02 ENDOSCOPE FLUSHING

The QRT02 endoscopes employ mirrors inside the PV, which are expected to receive some degree of material deposition. To minimize the deposition and keep reflectivity high, the endoscope in AEA31 was equipped with a hydrogen flushing system which constantly feeds a small stream of hydrogen over the mirrors into the PV. As of OP2.1, this leak rate was measured to be $3.63\,\mathrm{mbar\,L\,s^{-1}}$ (QRT_20230424-event3) by running the flushing system in an unpumped PV. To maintain sufficient accuracy at the small injection rate, the measured pressure increase had to be corrected for the leak rate.

## XII. CONCLUSIONS

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