Progress in Development of ITER Diagnostic Pressure Gauges and Status of Interfaces with ITER Components

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Neutral gas pressure is one of the main parameters for a basic control of ITER operation. Diagnostic Pressure Gauges (DPGs) shall provide pressure measurements in the range from 10^{-4} Pa to 20 Pa with an accuracy of 20 % and a time resolution of 50 ms. In total 52 DPG sensor heads will be installed in 4 lower ports, 4 divertor cassettes and 2 equatorial ports. The overall DPG system has 15 interfaces with various systems and components of ITER. The DPG system is being developed including sensor head and front-end electronics. A test campaign aiming at validation of the system baseline design is currently ongoing. The measurement performance of a DPG sensor head prototype has been investigated for various parameters, such as electrode potentials, transparency of the acceleration grid and electron emission current demonstrating the possibility to measure pressures up to 20 Pa. Emission properties of several material candidates for the filament (hot cathode) have been studied during approximately three months of continuous operation. Filament samples made of tungsten with 2 % doping of ThO_2 and tungsten alloy with 26 % of rhenium coated with Y_2O_3 demonstrated most promising results. These cathodes required lowest heating currents for fixed electron emission current. Mechanical tests of these samples showed no detectable deformations for maximum heating currents in transient magnetic fields of up to 8 T. The already obtained as well as future test results will be used for further design optimization and integration of the DPG system into the ITER environment.

Keywords: ITER, plasma diagnostics, pressure gauge, hot cathode, experiment.

1. Introduction

During the conceptual design phase of ITER DPGs, ASDEX pressure gauges (APGs) [1] have been selected as the reference sensor type. These gauges belong to a class of hot cathode ionization gauges and successfully operate in present-day tokamaks and stellarators such as ASDEX Upgrade, DIIID, JET and W7-X [2].

Notable feature of these gauges is the arrangement of the electrodes along the axis parallel to force lines of acting magnetic field. On the one hand, at low pressures the sensitivity of the gauge is drastically enhanced by the application of a magnetic field. On the other hand, with the pressure increase the normalized output of the gauge gets flatter limiting measurement accuracy [3]. In order to ensure compliance of the DPG baseline design, described in Section 2, with ITER high pressure operating conditions at 20 Pa, a dedicated performance test has been performed. Outcome of this test is discussed in Section 3.

During the system level design phase of ITER DPGs, the filament has been identified as the most critical component primarily limiting the lifetime of the DPG head. According to the results of parametric finite-element (FE) analysis [4] the filament with a diameter of 0.8 mm and conventional shape for APGs i.e. “single spiral” [1] has been confirmed as the optimal one in terms of mechanical stability. For the chosen filament geometry tests, aiming at demonstration of reliability compliance with ITER environmental conditions, have been performed for several preselected filament materials. The operational margin has been assessed by identifying the minimum current required to produce sufficient emission of electrons over a period of three months and the maximum current in high magnetic field causing structural damage of the filament. Main results of performed reliability tests are discussed in Section 4.

For proper and reliable operation of DPGs, analogue electronics providing control and measure functions are needed. The electronics shall drive electric potentials of the DPG head electrodes, measure the ion and electron currents and control these currents via a feedback loop. Prototypes of individual modules covering above mentioned functions have been developed, tested and integrated in one system. Details of this development are given in Section 5.

2. Design and interfaces of the DPG head

Exploded view of the baseline design of the DPG head is shown in Fig. 1. Features of this design in comparison with APG are: the additional thermocouple for precise calibration of the gauge, the mounting bracket for the fixation of cables and easy installation of the sensor, cable tails providing reliable electrical connection, thick brazed filament and the baffle for thermalizing fast neutrals [5].

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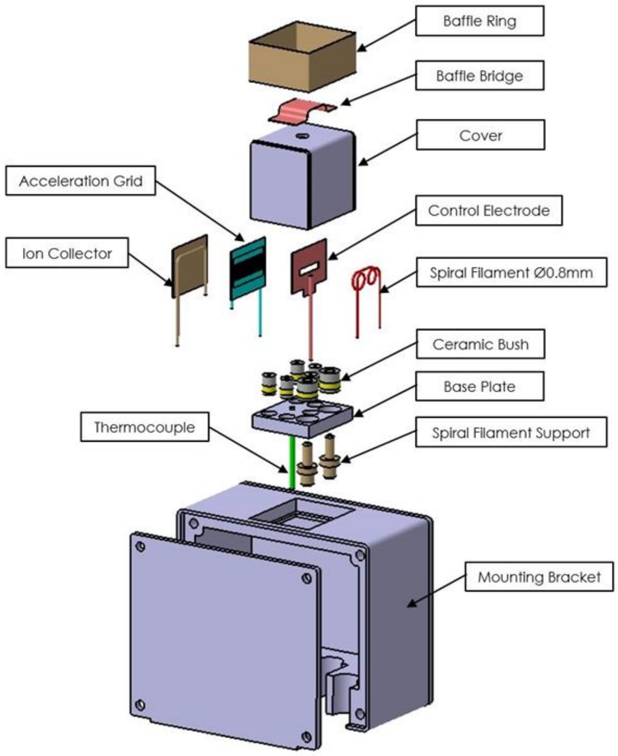

Fig. 1: Exploded view of the DPG head designed for ITER.

Internal mechanical and electrical interfaces of the DPG head have been defined; a new design of the mounting bracket and accommodation of signal and power cabling inside it were proposed (see Fig. 2).

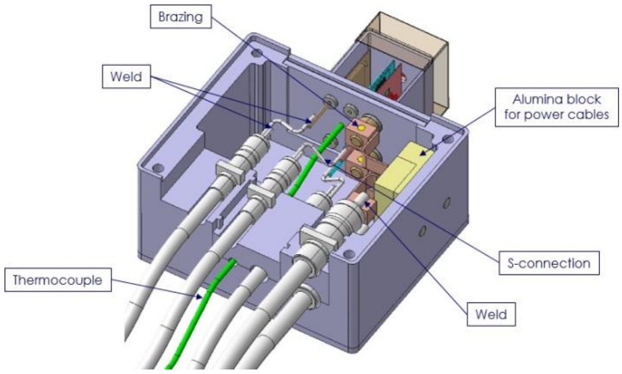

Fig. 2: Internals of the DPG head configuration “0°”.

As shown in Fig. 2 molybdenum filament supports are connected with the cable termination by means of copper straps which are brazed to the supports and welded to the cable terminations. Alumina blocks serve to counter Lorentz forces. In order to withstand torsion, cable connectors have joints with a square cross section. Signal cables are not insulated. Their connections are done by welding S-shape pieces designed as short as possible in order to reduce capacitive crosstalk.

Depending on the position in ITER, either configuration “0°” shown in Fig. 2 or configuration “90°”, with a sensor head turned by 90° with respect to the mounting bracket, will be used. As mentioned in introduction, sensor electrodes shall always be aligned with the toroidal magnetic field. At the lower ports, DPGs with configuration “0°” will be attached to mounting bosses which are welded to the vacuum vessel. At the divertor cassettes and equatorial port plugs, DPGs with both configurations will be welded directly to ITER components.

3. Measurement performance of the DPG at high pressure

A series of tests have been performed at IPP with the aim to identify settings that allow pressure readings of up to 20 Pa in hydrogen gas. Testing was executed in a vacuum chamber inserted in the bore of the magnet producing magnetic field of up to 7.9 T (see Fig. 3). A prototype of the DPG head was placed in the center of the magnet where the magnetic field is maximum. Detailed description of experimental setup and testing procedure is given in [3].

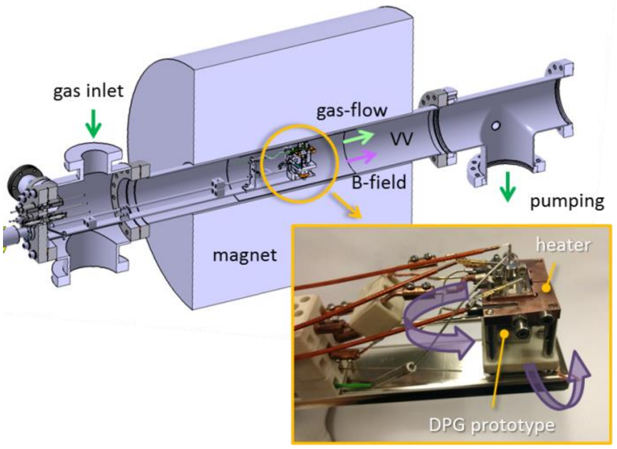

Fig. 3: Experimental setup for upper pressure limit test.

Measurements of the normalized gauge output in the pressure range from 10^{-2} Pa to 30 Pa for hydrogen gas and under variation of the magnetic flux density from 1 T to 7.9 T have been taken. Studying the influence of the electron emission current, the electrode potentials and acceleration grid transparency led to the conclusion that no parameter set demonstrated absolutely superior performance [3]. The reference configuration defined at system level design phase [5] is suited to fulfil the upper pressure limit of 20 Pa.

In all experiments on the measurement performance of the gauge the filament made of W-26%Re alloy and coated with Y_2O_3 was used as an electron source. It has to be noted that already after the first set of measurements the filament coating broke into small flakes and delaminated partially, especially at the hottest parts in the center of the filament, while the gauge prototype was able to operate stable. The reason of this delamination is not clear and will be investigated at the next testing phase.

4. Reliability tests

For reliability testing, different filament materials with promising characteristics have been chosen (see Table 1). On the one hand, the bulk material of the filament shall possess a high strength and high creep resistance at high temperatures. Tungsten and tungsten composites were the first choice due to their elevated melting point. On the other hand, the surface of the material shall feature a low work function, meaning that the required temperature to reach a sufficient electron emission shall be as low as possible. Low temperatures involve higher tensile strength in the material and low heating currents lead to less stress due to Lorentz forces.

4.1. Long term test on the electron emission capability of the filament samples

Long term emission characterization of filament samples was focused on validation of the ability to emit a stable electron current of 300 μA for at least 1500 h, which is the operational time of a single gauge during ITER life, within the required heating current range without additional loads from the magnetic field and without gas injection.

Filaments were clamped into a specific prototype by screws in the filament supports. Two prototypes with different filament samples were inserted in the vacuum chamber at the same time (see Fig. 5).

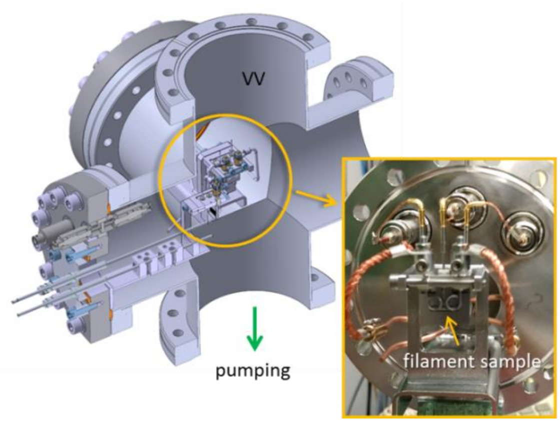

Fig. 5: Experimental setup for long term emission test.

After installation of the prototypes, the chamber was pumped by a turbo pump until the pressure reached $<10^{-5}$ Pa. The electron emission current was stabilized with a feedback-controlled power supply to heat the filament. During the experiment, information about the electron emission current, the filament heating current, the voltage drop across the filament and the pressure in the vacuum chamber has been recorded. Values of the required heating current at the end of the experiment for tested samples are given in Table 1.

Table 1: List of materials for the long term emission test and heating current at the end of the testing period

Material of tested filament sample	I_h at the end of test
1. W doped with 2% ThO_2	25 A
2. W-26%Re alloy coated with Y_2O_3	14.5 A
3. W doped with 0.4% ThO_2 and 70 ppm K	26 A
4. W coated with Y_2O_3	19.5 A

Fig. 6 indicates the data recorded during operation of W-26%Re filament coated with Y_2O_3. After more than 1600 hours of continuous operation required heating current has been reduced more than on 5% and towards the end of experiment reached lowest value among all tested filament materials.

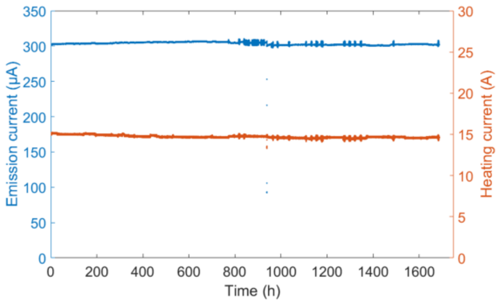

Fig. 6: Electron emission current and required filament heating current during long term emission experiment of W-26%Re filament with Y_2O_3 coating.

4.2. Mechanical rupture and deformation tests of filament samples

Since DPGs will operate in strong magnetic fields, their filaments shall sustain significant Lorentz forces caused by the heating current flowing perpendicular to the magnetic field direction. At the same time, the filament is heated to high temperatures by ohmic power dissipation and, thus, weakening the mechanical stability. In order to document the physical reaction of the heated filament under magnetic fields of up to 7.9 T, a mechanical rupture and deformation test has been executed.

The prototype with pre-installed filament sample was mounted at the center of the vacuum chamber in a similar way as for the upper pressure limit test (see Fig. 3). The chamber was pumped until the pressure reached $<10^{-4}$ Pa. At first, the filament was heated with a constant current in feedforward mode to reach thermal equilibrium and the magnetic field pulses were applied consecutively.

The behavior of the filament was observed with a CMOS camera. In order to detect the deformation of the filament, an additional grid serving as a reference pattern was installed in front of the filament (see Fig. 7). A mirror placed beneath the filament with an angle of 45° allowed to observe the filament from the front and top perspective at the same time (see Fig. 7).

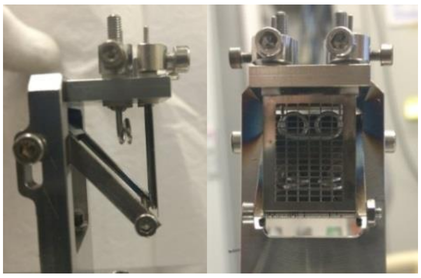

Fig. 7: A photograph of the set-up for the mechanical rupture test showing the prototype from the side (left) and the front (right), as seen from the camera during the experiment.

The first three samples indicated in Table 1 have been tested. Heating currents of up to 30 A were applied for samples 1 and 3. In order to avoid damaging the coating, the maximum applied heating current for sample 2 was reduced to 21 A. In all cases neither plastic nor elastic deformations of filaments have been observed.

5. Development of the DPG electronics

Based on the results of the system level design [5], an integrated electronics system for the DPGs operation has been developed (see Fig. 8).

Fig. 8: Photograph of the electronics system providing operation of one DPG head.

The system includes external power supplies for filament heating and biasing electrodes of the gauge and an electronics crate carrying the interface card to a plant system controller (PSC), power supplies providing operation of electronics and printed circuit boards (PCBs) holding following "core" components: ion current amplifier (ICA), electron current amplifier (ECA), control electrode switch (CES), thermocouple measurement (TCM) and filament heating control supervision (FHC) (see Fig. 9).

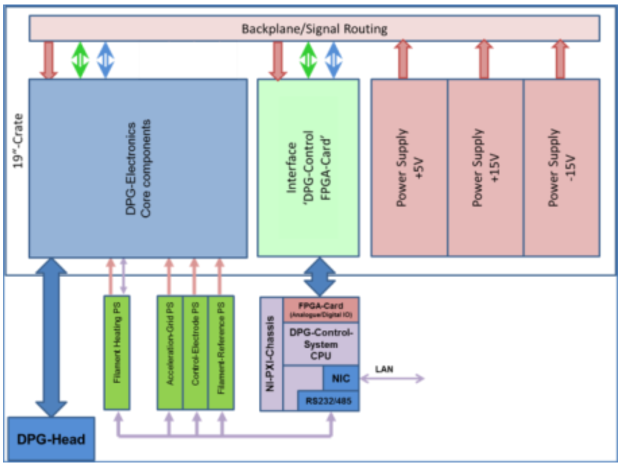

Fig. 9: Block diagram of the DPG electronics system.

The developed DPG electronics have been coupled with already existing PSC and used for testing a DPG head prototype at various hydrogen pressures with and without magnetic field. The length of the used signal cables was 200 m, which corresponds to the maximum cable length in ITER. To avoid oscillations on the electron current signal, the grounding scheme has been optimized. In the accessed pressure range, measurements of the ion and electron current showed a flat-top within the required criteria and, therefore, the test was considered successful. Test results are comparable to the performance of electronics deployed for operation of APGs at ASDEX upgrade. However, the ion current signal for prototypes features oscillations with the highest amplification stage. This may lead to erroneous measurements in the low pressure range ($<10^{-2}$ Pa) and, thus, further optimization is required.

6. Conclusions and future work

The presented test results demonstrated that the required upper pressure limit of 20 Pa is achievable [3]. At the same time, the requirement on the measurement accuracy of 20 % shall be fulfilled. This can only be estimated if the reproducibility of the signal is known. These measurements are foreseen for the next phase of the design.

In terms of reliability performance W-26%Re filament with Y_2O_3 coating has been recommended since it demonstrated lowest heating current and the temperature required to operate for >1500 h and successfully passed mechanical rupture and deformation test. Dedicated test aiming at studying of delamination of Y_2O_3 coating at the surface of W-26%Re filament have been planned.

The structural integrity assessment of all DPG configurations including the DPG sensor and the mounting bracket with internals and cable tails have been performed assuming operation of W-2%ThO_2 filament at 25 A of heating current and a temperature of 2173 K. The structural integrity could be validated for almost all combinations of loads and design configurations. However, the reduction of filament heating current has been recommended in order to increase the margins. In particular, reduction of the heating current to 20 A and respective temperature to 1900 K will further reduce the probability of a filament failure due to creep as hinted at by analysis. This has to be confirmed experimentally since some of the available material properties, which are used for the calculations, have a rather high level of uncertainty. Thus, conservative rules were used for the assessment and creep tests will be performed to benchmark analysis results.

Another mechanism potentially limiting the lifetime of DPGs is a fatigue failure caused by repeated start-ups of the gauge in a magnetic field. It is difficult to assess fatigue theoretically since this mechanism incorporates many material properties which are not known a priori. Additionally, there is almost no relevant data available in a public literature. In order to validate the capacity of the DPG to withstand repeated application of the combined thermal stress and Lorentz forces resulting from the 3000 operational cycles as defined by RAMI analysis, simultaneous testing of 12 DPG prototypes will be performed in the JUMBO facility at KIT equipped with a superconducting magnet allowing a steady state operation at 8 T.

Acknowledgments

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