TECHNICAL NOTE

IN SUPPORT OF THE MARKET SURVEY TO IDENTIFY

TEST RIG FACILITIES FOR CALIBRATION OF THE ITER PRESSURE GAUGES

Contents

1. Introduction

F4E is launching a Market Survey to identify existing test rigs with a magnetic field up to 8 Tesla and that could be adapted to meet the ITER Pressure Gauge (hereinafter DPG) calibration requirements.

Please note that test rigs with lower magnetic field (~6T) would be also considered in case a combined strategy is implemented to provide the full calibration curves.

This Technical Note aims at providing support information to allow a first assessment on the capacity of existing test rigs to adapt to the requirements for the DPGs calibration.

2. The ITER Pressure Gauges

The ITER pressure gauges, henceforth called DPGs, are ionization pressure gauges that provide measurements of the neutral gas pressure in the ITER divertor, lower ports and the main chamber wall.

These measurements will contribute to the basic control of ITER. The pressure measurements are used to assess the efficiency of the ITER divertor in compressing neutrals and are also used in the early phase of a pulse to diagnose plasma initiation).

The DPG comprises 52 individual gauges assemblies distributed poloidally and toroidally within the torus vacuum.

The gauge head consists of a heated cathode (CAT) for electron emission, a control electrode (CE), an acceleration grid (AG) and an ion collector (IC). The CE has a rectangular opening to let the electrons pass if the potential is high enough. If the potential is lower than the CAT, electrons are blocked. Once electrons pass the CE, they are further accelerated by an electric field, a portion passes the grid of the AG and overshoot into the volume between AG and IC, where they may ionize gas atoms. The ions are attracted and collected by the ion collector. The electrons impinge eventually on the acceleration grid. Both currents are measured by special electronics circuitry which is wired to the electrode pins below the base plate. A thermocouple of type N (TC) is fixed to the base plate. The tip of the sheath is located inside the base plate between the ion collector and the acceleration grid.

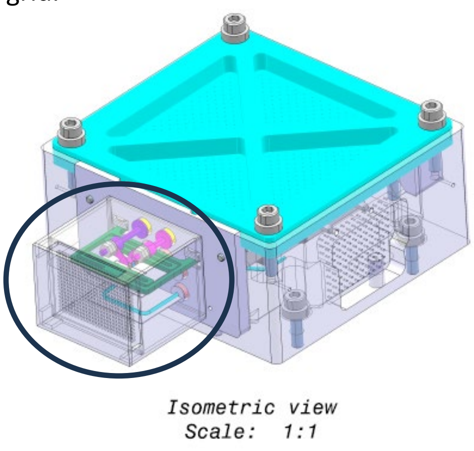
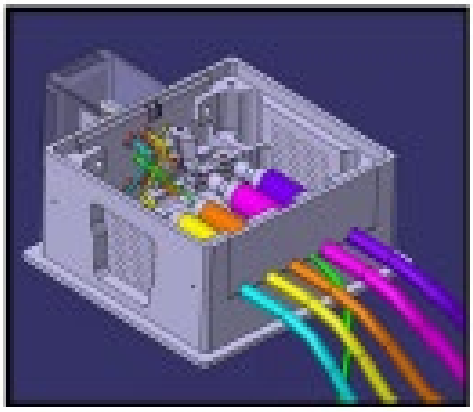


Fig 1. DPG assembly with the connection box. The sensor head which will require calibration is encircled.



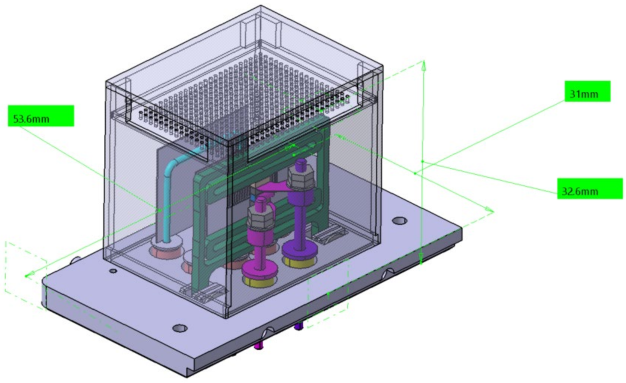
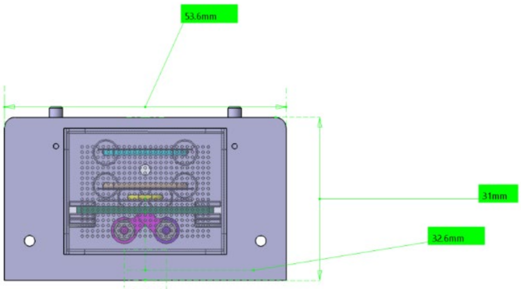


Fig 2 DPG assembly with cables connected.   Fig 3 DPG head & head housing assembly (90º)



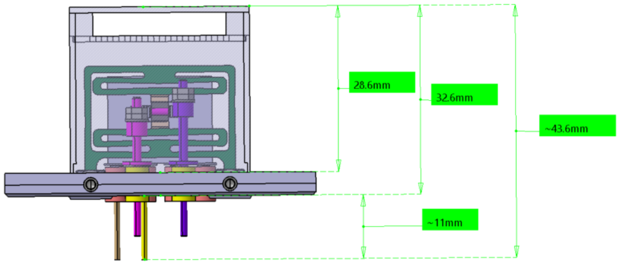


Fig 4 Botton and lateral view of the DPG head & head housing assembly mounted onto the baseplate.

The DPG heads assemblies including housing will require to be calibrated, example of DPG assembly can be seen in fig 3. Complementary views in fig 4 provide information about the size of the items to be calibrated. There are two configurations, 90 º as in the fig 3, or 0 º, which has the sensor head rotated additional 90º.

3. Calibration of the DPGs

The DPG sensitivity is defined as $s = \frac{I_i}{I_e - I_i} \cdot \frac{1}{p}$ (1)

where Ii and Ie denote the measured ion and electron current respectively and p is the pressure. The electron current is held at a constant value by a feedback regulation implemented in the controller.

The DPGs will be operated with different parameters depending on the pressure range they are deemed to operate in (divertor gauges are located in a different pressure environment than equatorial port gauges). The difference is related to the bias voltage of the grids and the electron current as shown in the table below:

Name of the parameter settings	Valid pressure range (Pa)	Cathode voltage U_{cat} (V)	Control grid voltage U_{CG} (V)	Acceleration grid voltage U_{AG} (V)	Electron current Ie (µA)
Low pressure - LP	$10^{-4} – 1$	70	0-160 @ 1kHz	250	800
High pressure - HP	$10^{-2} – 20$	100	0-160 @ 1kHz	195	100

Table 1: Voltage settings of the DPG head for indicated pressure ranges

In both cases, the control grid voltage is periodically switched from 0 V to 160 V with a frequency of 1 kHz. This is important to subtract parasitic currents which change on a timescale greater than a millisecond.

In addition, the sensitivity is not only a function of the pressure but it also changes with the magnetic flux density and thermal condition of the gauge head. Depending on the location, the maximum magnetic flux density will vary.

The curves produced during calibration will allow to extract the pressure for a given magnetic field.

Obtaining continuous calibration curves for the relevant pressure ranges is needed.

The measured signal will allow to obtain the sensitivity.

s = s(Ii/(Ie-Ii))

The gauge signal divided by the sensitivity will provide the pressure.

$$p = \frac{I_i}{I_e - I_i} \cdot \frac{1}{s}$$

Regarding temperature, its effect is well known. Calibration shall be done at stable constant temperature. During operation in ITER, the real pressure will be obtained applying the temperature correction:

preal = pmeas*sqrt(Treal/Tcal), where Tcal is the temperature during calibration.

All DPGs will be calibrated in D2, and if the expected correlation is demonstrated, only a reduced number will be also calibrated in H2 and He.

All gauges require calibration at low pressure range, gauge head for divertor and lower ports require also calibration at high pressure range. Pressure ranges and setting parameters during calibration are indicated in table 1.

The DPG heads shall be calibrated at the magnetic flux levels indicated per DPG , only 8 out of 52 will undergo more than 6T.

All measurements shall be done at a constant temperature (ref:250C) monitored at the baseplate with a thermocouple.

$$T_{BP} = 250°C \pm 5°C$$

Appropriate provisions have to be foreseen to keep the device within these boundaries. (E.g: vacuum compatible heating cartridges inside the holder of the DPG head and a good thermal connection to the flange)

Baking of the vacuum vessel and DPGs is required before starting the calibration in order to be able to achieve the base pressure conditions, as well as to maintain heating to reach the required thermal equilibrium.

Reference temperatures and duration are: outgassing at 350°C for two hours of the DPG head and at 250°C for at least 5 hours before start of measurement.

Reference steps for the procedure for calibration against pressure at constant magnetic field are given below:

1. Energize coils of the magnet as required to reach MFD at gauge position
2. Activate gas inlet and valves as required – according to LP or HP range
3. Pump to base pressure (<5e-6 Pa for LP and <1e-4 Pa for HP). Allowed rest gases: H_2, H_2O, CO, CO_2; partial pressure of other gases must be lower than 1e-8 Pa
4. Set potentials of electrodes as required (LP or HP settings)
5. Start cathode operation in feedback mode as required (LP or HP settings)
6. Let the gauge run for 2 minutes to reach thermal equilibrium inside the gauge head
7. Start pressure ramp at lower end to cover the required pressure range using an exponential increase rate: 1.5 - 2x per 90 s starting from 5e-5 Pa (LP) or 1e-3 Pa (HP).
   Continuous gas flow shall be maintained to avoid contamination of polluting gas components.
8. Pump the vacuum vessel down to base pressure
9. Switch the gauge off
10. Change conditions for the next magnetic level or working item

4. Test Rig requirements:

4.1 Requirements to the magnet

- Magnet shall be able to provide the magnetic field required. B ≤ 8 T homogeneous for +/- 1 % in a sphere of 2.5 cm diameter around ROI, preferably superconducting allowing continuous operation and helium recovery.
  In case that more than 1 DPG is calibrated simultaneously, the homogeneous magnetic field region shall be ensured around each DPG.
- Warm-bore diameter shall be enough to fit in the stainless steel vacuum pipe. Thermal insulation is required if a cold-bore exists.
- The power introduced shall be considered for the warm-bore heating limitations.

(As reference not more than 100W were required in DMag test facility during the calibration test campaign)

4.2 Requirements to the vacuum vessel /vacuum /gas system:

- Pipe cross-section shall fit in the magnet bore and shall house the DPG/DPGs with their holder, heaters and cabling. Constrains as the space and gas conductance shall be taken in account.
  DN100 pipes have been used during the design phase, smaller diameters might be possible but challenging.
- Bake-out: All parts bakeable to T ≥ 120°C
- Provisions to bake the vacuum vessel to at least 100°C
- Residual gas analyzer must be present (0-100 amu)
- Total base pressure without gas inlet: p < 5e-6 Pa . Allowed rest gases: H_2, H_2O, CO, CO_2; partial pressure of other gases must be lower than 1e-8 Pa
- Pump configuration shall allow to reach the base and residual gas pressure requirements and allow continuous gas flow to avoid polluting accumulation.
  Pumps shall be certified for use of the calibration gases. Pumps shall be oil free.

  Reference pumps:
  Turbomolecular pump; pumping speed ≥ 300 l/s
  Oil-free roughing pump; ATEX-certified for pumping of hydrogen and deuterium gas

- Valves shall allow bypass or regulation of gas as needed during calibration.

  Reference valves are:
  Gate valve to turbomolecular pump with bypass and remote-controllable gas reduction valve
  2 gas inlet valves with remote-controllable gas flux (back end and in front of the gate valve)

  The supplier shall provide the control and data acquisition system of the vacuum and gas system.

4.3 Requirement to the flanges, electrical feedthroughs and the in-vessel electrical cabling

- Feedthroughs shall be present to allow passing the in-vessel electrical cabling.
- The supplier shall provide UHV compatible and high temperature resistant in vessel electrical cabling compatible with table 1 parameter settings:
- 3 individually screened signal lines (coaxial preferred) HV rating 250 V
- 2 power lines with a min current rating of 15 A and HV rating of 100 V
- 2x power line for base plate heaters (requ. depent on heater specification (reference100 V and 2 A)
- 2x thermocouple lines type N.
- All flanges closed using copper gaskets (no viton seals)

4.4 Requirements to the reference pressure gauges

- The reference gauges used for calibration shall cover the range 1e-6 Pa to 50 Pa with a relative accuracy of < 4 % for each pressure measured.
- Additionally, one gauge shall be able to measure up to atmospheric pressure.
- Accuracy shall be justified for each range of pressure with the calibration certificates of the gauges used in that range.
- Cross calibration shall be implemented in case calibration certificates are not available for some gauge.
- Cross calibration using previously zeroed capacitance gauges shall be performed regularly for some gauges as the Bayard Alpert Gauges.
- Redundant reference gauges shall be provided per each range of measurement.

The gauges configuration below is provided as reference:

- 4x Capacitance gauges (e.g. MKS Baratron) accuracy: ≤0.25 % of reading and ≤0.01 % of full scale
  - 2x gauges with 1 – 5 Pa full scale (or lower)
  - 2x gauges with 50 – 100 Pa full scale
- 2x Bayard-Alpert gauges accuracy, magnetically screened
  - Cross-calibration against capacitance gauges needed at 0.01 – 0.05 Pa
- 2x cold cathode gauges, magnetically screened
  - Cross-calibration against capacitance gauges needed at 0.01 – 0.05 Pa
- 1x Pirani gauge, 100 kPa full range

Location and protection of the reference pressure gauges:

- Reference pressure gauges shall be installed upstream and downstream of the DPG location. It shall be demonstrated that the pressure at the reference pressure gauges location is representative of the DPGs location. Difference shall not exceed 5% in the whole pressure range.

- The effect of the magnetic field shall be limited either by distance or shielding.

4.5 Requirements to the DPG head mount

- The DPG head mount holds the DPG head physically at a pre-defined position inside the magnet.
- The DPG mount can hold one or several DPG heads depending on the space in the test rig.
- It connects the flange incl. the feedthroughs with the attachment jig for the DPG head
- It leads the cables from the feedthrough to the DPG head
- Serves to guide heat from the DPG head to the flange
- The attachment jig shall contain heating elements to heat the DPG head up to a temperature of 400°C
- The DPG head needs to be aligned with magnetic field, that is the planes of the electrodes shall have a 90°± 3° angle to the direction of the magnetic field
- The gauge heads can have two different orientation (“0°” and “90°”), possibly two different mounting jigs are needed to place the gauge head with the correct orientation into the magnet.

4.6 Requirements to data acquisition

F4E will deliver a portable data-acquisition system (hardware and software) that enables the control and acquisition of data from the DPG. The system will also integrate the environmental measurements described below (which will be provided by the Supplier).

The portable data-acquisition system will implement the following features:

- DPG front-end electronics and controller

    - Electron current
    - Ion current
    - Cathode voltage
    - Upper voltage of control grid
    - Acceleration grid voltage
    - Cathode heating current
    - Ion current amplifier settings
    - Thermocouple temperature

- Electronics interfaces (endpoints) to connect the environmental measurements that are to be delivered by the Supplier
- Operator software interface to:
    - Set and retrieve the gas sort and other operator relevant information
    - Operate and store data from the DPG electronics
        - Demodulated electron current
        - Demodulated ion current
        - Thermocouple measurement
        - Electronics status and error information
    - Acquire and store data - at a rate of at least 20 Hz - from the environmental measurements that are to be delivered by the Supplier.
        - These acquisitions will be synchronised to the DPG measurements, to ensure consistency and accuracy in the recorded data.
    - Download the data files with the data acquired from the DPGs and from the environmental measurements. T
        - The data file will include the gas sort, the date and start-time as part of the header of the delivered data file

At the test rig it shall be made available the following environmental measurements

- Solenoid current and/or magnetic flux density measurement at DPG head
- Vacuum vessel temperature at wall close to the DPG head
- Pressure measurements of all pressure reference gauges

All the environmental measurement devices shall provide an instrumentation interface (digital or analogue), so that they can be integrated in the portable data acquisition. The exact definition of such interfaces shall be made available by the MRR.

4.7 Requirements to the ex – vessel cabling:

The interface between the portable data acquisition system and the DPG is implemented using a feedthrough on the vacuum flange.
F4E will provide a cable loom with a special connector to interface with the portable data acquisition system on one end, and providing the following individual cables on the other end:

- 1x filament powering cable (15 A max., 150 V max, with e.g. banana connectors)
- 3x coaxial signal lines (RG 58, with e.g. BNC connectors)
- 1 x thermocouple cable type N (standard TC connector).

The portable data acquisition system must be placed in a region sufficiently far away from the magnet with a magnetic field of < 1 mT. The length of the cable loom and the exact cable termination (e.g. BNC connectors) shall be specified. With this information, F4E will terminate the cables with the agreed connectors so that they can be connected at the test rig to the flange.
In case several DPGs can be set in the vacuum vessel, a switch to change the connections with the portable data acquisition would allow the calibration of one DPG after the other without opening the vessel.

5. Tentative Schedule

The estimates below intend to provide an idea of the schedule and duration required. Please note these are tentative values that might change in the future.

- Technical dossier preparation to adapt an existing test rig to the requirements above should start mid-2026.
- Purchase of items, test rig adaptation activities and commissioning are aiming to start the calibration in the second half of 2027.
- Duration of the calibrations will depend on the number of gauges calibrated simultaneously, but with a full dedication of the calibration rig and calibrating one gauge at the time, the full calibration would then require half a year.

6. Market Survey

Please answer the Market Survey by clicking this LINK.