TECHNICAL DESCRIPTION FOR THE LEAK DETECTION SYSTEMS for ITER PRIMARY VACUUM SYSTEMS AND ITER CRYOSTAT

Abstract

The experimental fusion reactor ITER will require a leak detection system for primary vacuum systems and another one for the Cryostat vacuum system.

This document describes the Primary Vacuum leak detection system (PLDS), PLDS includes the direct leak detection stations for the Torus vacuum vessel and the Neutral beam, which are used during short and long-term maintenance periods of ITER torus and remote leak detection stations in the VPR (Vacuum Pumping Room), which are used for continuous monitoring of a gas coming from torus during machine operation for any abnormal fluctuations.

Gas calibration station which is linked to the torus direct leak detection station provides calibrated gasses for calibration of leak detection instrumentation while gas calibration stations situated in the VPR are used for continuous exhaust gasses monitoring for detection of gasses associated with leaks (other than helium). It could also be used for tritium measurement.

A Call for Tender for the preliminary and final design, manufacturing, testing and shipment of the components that make up this system will be launched at the second half of 2019. With the aim to complement market survey performed in June 2018, this report outlines the design of the systems as well as the procurement schedule and strategy.

F4E Reference	**F4E_D_**

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1. Introduction

The Leak detection system for ITER is divided in 3 main systems listed below:

- the Primary Leak Detection systems (PLDS);
- the Neutral Beam LD system (NBLDS);
- the Cryostat LD system.

These 3 systems will allow detecting leaks in any of ITER components connected to the main torus vacuum, in the neutral beams vacuum systems and in the Cryostat vacuum system.

Associated to this system there will be some auxiliary systems to calibrate for use in ITER the leak detection instrumentation. And also there will be a Gas Analysis system which will enables to get the compositional analysis and activity measurement of a gas sample.

These 3 systems are split as follows to give the whole functionality of the Leak Detection systems to ITER machine:

a) Torus Vacuum Direct Leak Detection system which provide He leak detection capability to the main vacuum vessel.

b) Neutral Beam Direct Leak Detection system which provide He leak detection capability to the vacuum system used at the neutral beam components.

c) Remote Leak Detection systems, which provide He leak detection to different systems (active service vacuum system, Torus Vacuum, Neutral Beam and Cryostat) thought a continuous monitoring of the He signal into each roughing line of the system.

d) Gas Analysis system enables compositional analysis and activity measurement of a gas sample (typically traces of hydrocarbons, He, Q2, Ar, O2, N2, CQ4, CO should be measured by this system.

e) Leak Calibration system which provides a specific and accurate mass flow of different gases in order to calibrate the different mass spectrometers on the leak detection units.

f) Cryostat leak detection which will provide He leak detection capability to the vacuum system of the whole cryostat.

The design of the Leak Detection systems for primary vacuum and Cryostat are currently more mature than a Conceptual Design stage. Technical specifications, PFD’s and P&ID’s are also available at that stage. Those diagrams should define the main functionality of each system, but layout, components could be changed while design is evolving.

A Call for Tender for the preliminary and final design, manufacturing, testing and shipment of the PLDS, NBLDS and CLDS systems will be launched by mid-2019.

This technical description pretends to give the main technical information in order to allow suppliers to dimension the engineering team to cope with the design tasks for the preliminary design review foreseen in October 2021 and final design review in May 2022.

At a later stage, according the procurement strategy, the components/modules could be procured independently, combined, or all together as a single Engineering & Production contract.

2. Design overview

2.1. Scope

The overall scope of the procurement includes preliminary and final designs, procurement, manufacturing, assembly, factory acceptance testing and shipment to the ITER site in Cadarache (France) of:

Three LD systems with the related gas analysis and gas calibration systems for the ITER:

- o Primary vacuum systems (PLDS): direct and remote
- o Neutral Beam system (NBLDS): direct and remote
- o Cryostat vacuum system (CDLDS): direct and remote

A conceptual design was passed satisfactory in 2014 for all sub-systems, outcomes from that review allows to prepare all documentation to progress with the design up to the final design review.

Installation and on-site testing is outside of the scope, but Installation operation and Maintenance (IOM's) should be also delivered under the scope of this contract.

The analyses for the final design include structural analyses (including seismic loads), conductance and effective pumping speed calculations and any further analyses as required by the applicable standards:

- ASME VIII Div 2 for design and structural analysis of the vacuum components (despite not being a pressure vessel).
- ASME B31.3 (Cat M) for piping design, manufacturing and testing

All LD&LC systems should be compliant with some specific vacuum requirements defined in the ITER vacuum handbook [1].

2.2. Operation

There are two different types of leak test with different leak rate requirement: PIA (Protection Important Activity) and operational ones. Overall operational requirement is to ensure no air equivalent leak higher than 1.10^{-10} $Pa.m^3/s$ (1.10^{-9} mbar.l/s) goes into VV and this is 3 orders of magnitude lower than the safety leak rate that should be guaranteed under the all load combinations. Despite that, the LD unit shall be equipped with a mass spectrometer, which could detect minimum leak rates ≤ 1.10^{-11} $Pa.m^3/s$.

Leak testing will be carried out in three stages:

1. During assembly at ITER site;

2. After completion of assembly and during commissioning;

3. After start of plasma operations.

The main industrial safety issues relevant to the PLDS are primarily fire and the risks associated with handling pressurized gases, asphyxiation and/or flammability (fire hazard).

The hazards associated with gas handling are addressed by high containment integrity achieved by using best industrial practise, gas and low oxygen detection, dispersion by ventilation systems and through the specification of appropriate equipment.

2.3. Description

Primary leak detection and localization system consists of the following sub-systems:

Primary vacuum leak detection system
Primary vacuum leak detection system comprises of the following sub-systems:

- Torus direct Leak Detection Station (shown in Fig 1)
- NB direct leak detection station (shown in Fig 2)
- Remote Leak Detection station(s) (shown in Fig 4)
- Cryostat direct Leak Detection station (shown in Fig 3)

Supporting systems / Tools
- Calibration station (which PID is shown in Fig 8)
- Gas analysis station (which PID is shown in Fig 9)

The subsystems of the PLDS, their functions and features are summarized in the Table 1.

Station	Function	Features
1. Torus (direct) leak detection station TDLD	Helium leak detection for qualification of containment boundary for operations and safety function.	Fast response time for helium, may be used during operations depending on magnet status, mainly for use during maintenance.
2. NB (direct) leak detection station		
3. Cryostat (direct) leak detection system		
4. Torus, (slow), leak detection station (remote-pumping room)	Helium leak detection during operations	Continuous monitoring station with magnets energised.

5. DNB/HNB, (slow), leak detection station (remote-pumping room)		
6. Service Vacuum System (SVS), cryostat (slow), leak detection stations (remote-pumping room)		
7. Gas calibration station (local to Torus)	Provides calibrated gasses for calibration of leak detection instrumentation	Gas mixtures for quantitative calibration of Residual Gas Analysers (etc.)
8. Gas analysis station (remote-pumping room)	Continuous monitoring of exhaust gasses for gasses associated with leaks (other than helium)	Includes Neon, Argon, Air detection system

Table 1. Leak detection subsystems

2.3.1. Primary vacuum leak detection system

1. Torus direct Leak Detection System description

Torus direct leak detection station (TDLDS) comprises a leak detection station that should be installed in the balcony of HNB3 cell at L1 for the Torus vacuum Leak Detection System, and the Neutral Beam Leak Detection System located on the NB HV deck at L3.

If a leak is suspected then helium is supplied to the vacuum vessel interiors by SVS spraying tubes and will be detected on the mass spectrometer calibrated for He.

This system will be the first to be installed, and will not have any requirement on radiation resistant for any of the components listed below:

- DN 500 and DN 300 reducer between the bellows and pumping manifold (including electrical baking and control)
- Pumping manifold DN 300 with 4 DN 250 CF port connections for the turbo molecular pumps.
- MS leak detection unit (described in § 2.3.2)
- All metal valves, double and single contained.
- Process compatible turbo molecular pumps
- Component support frame(s)
- Flexible hoses
- Vacuum pipework and connections
- Seals for demountable joints
- Installation procedures (IOM's)
- Commissioning procedures

A view of the 3D model of Torus direct Detection Station and the space reservation for the electrical cubicles is shown in figure below for the non-active phase in HNB3:

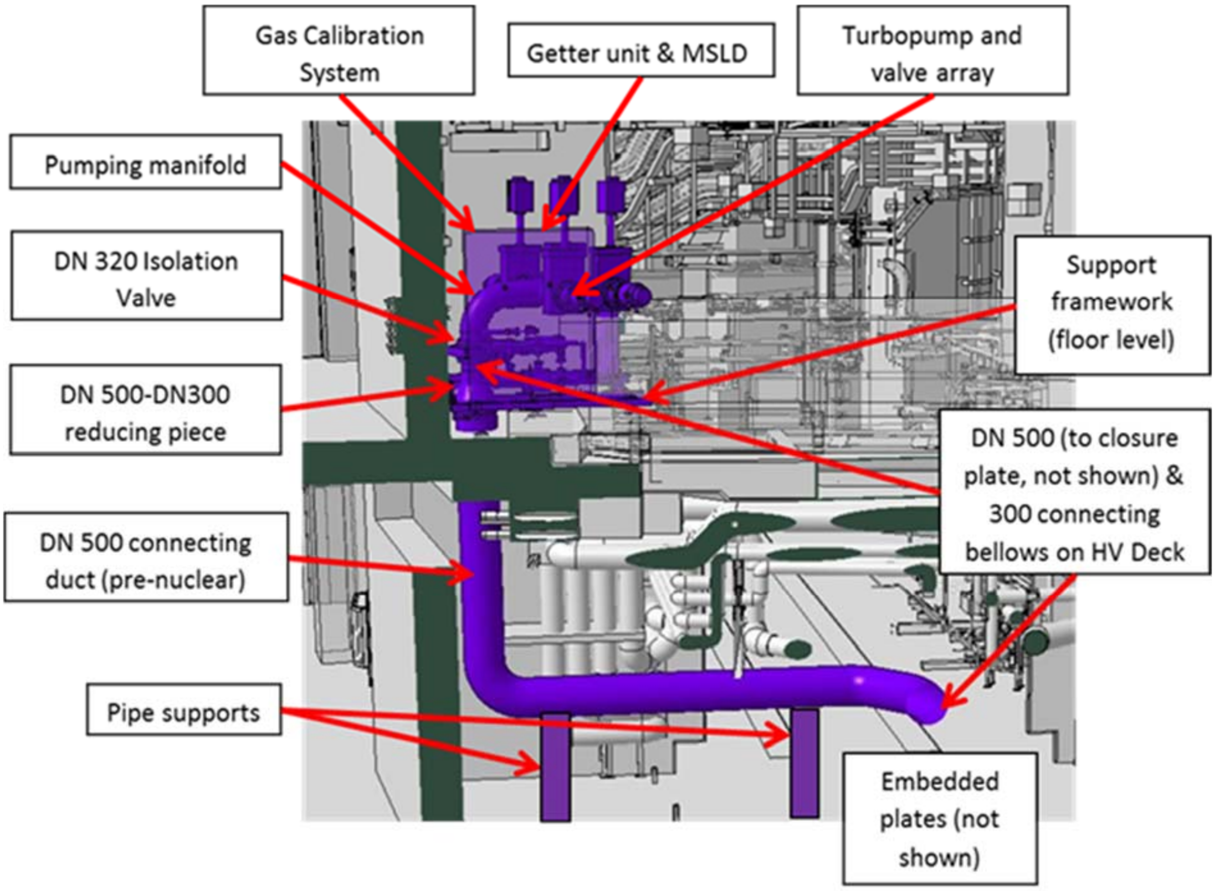

Figure 1 - View of the 3D model for the TDLD (pre-nuclear phase) at balcony HNB3

TDLDS comprises the array of Turbomolecular pumps with inlet manifold with sufficient conductance to provide response time lower than 15 minutes. Also all supports required should be designed and verified against the different load specification given at each location (see § 2.3.2)

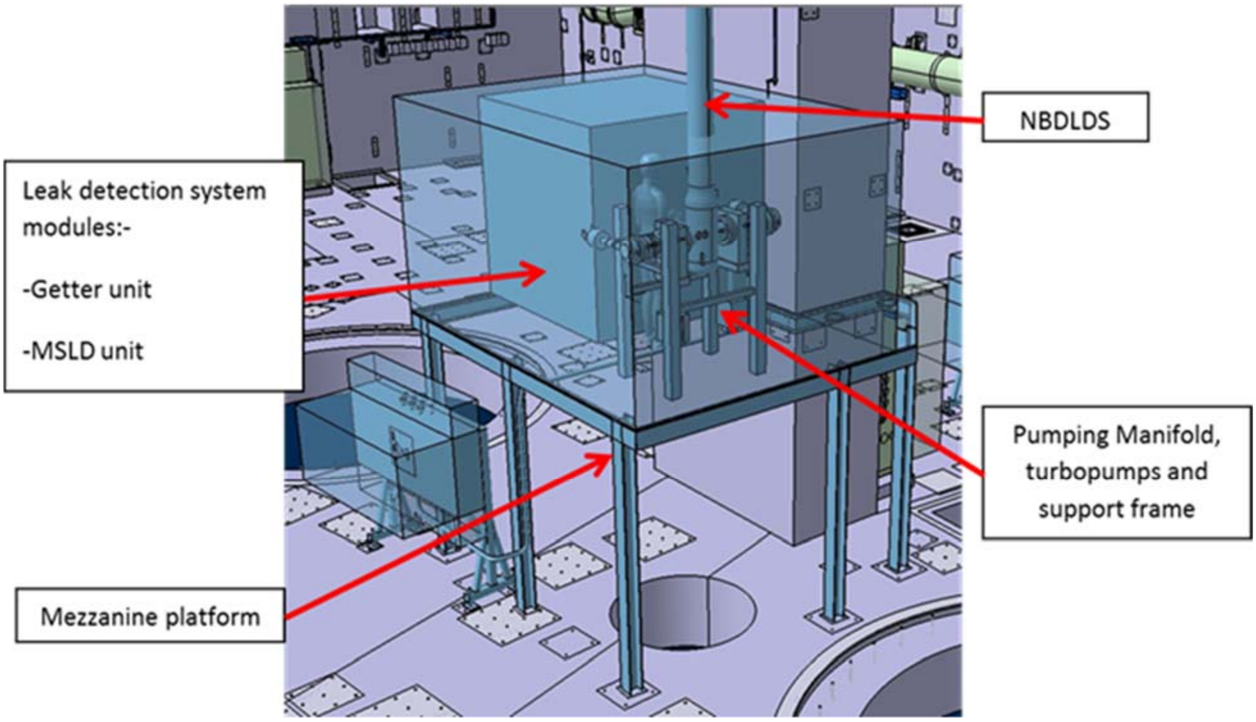

Figure 2 - View of the 3D model for the Neutral Beam (direct) LD system at NB HV deck at L3

2. Remote Leak Detection Systems description

Remote leak detection station provides a continuous monitoring of the gases coming from the torus vacuum and it can operate during plasma operations, where direct leak detection station can’t work because magnetic field is too high for the turbopumps. If a leak is suspected then tracer gas (for example helium) is supplied to the torus vacuum interiors by spraying tubes of SVS.

Remote leak detection stations are sited in the Vacuum Pumping Room (VPR) located in the Tritium building. Four identical leak detection stations presented below are connected to the torus roughing and Torus CryoPump regeneration foreline, NB roughing and regeneration foreline, non-active and active SVS roughing forelines:

- Torus remote leak detection station (also provides leak detection services for NB Absolute valve and Type 2 Diagnostics);
- NB remote leak detection station;
- Non-active SVS and cryostat leak detection station;
- Active SVS leak detection station.

Mass spectrometer Leak detection station will be connected to roughing line for baking; no internal baking pump will be required. Current version of remote leak detection station PID for Torus vacuum showed in Fig.5. Leak detection stations for NB and SVS are presented in the Fig 6 and 7.

All those leak detection units should be fit in a glove box, providing that a secondary physical barrier shall be installed for components which potentially could be in contact with Tritium (radioactive isotope). The design of these glove boxes should also provide maintenance operations on the vacuum pumps and other components which require maintenance operation.

Depending on the experience of the supplier, the design and procurement of these glove boxes would be an option of the current contract. Either F4E will execute this option, or this part of the scope will be managed directly by F4E.

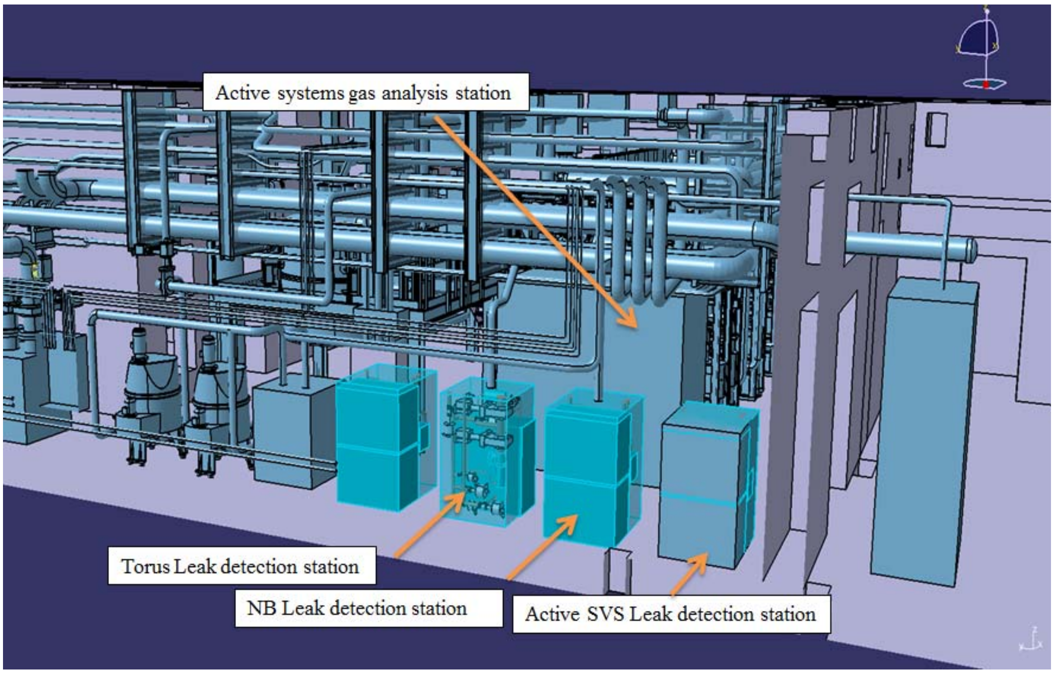

Figure 4 - Location of remote leak detection stations and active gas analysis station in the Vacuum Pumping Room (VPR) of tritium building

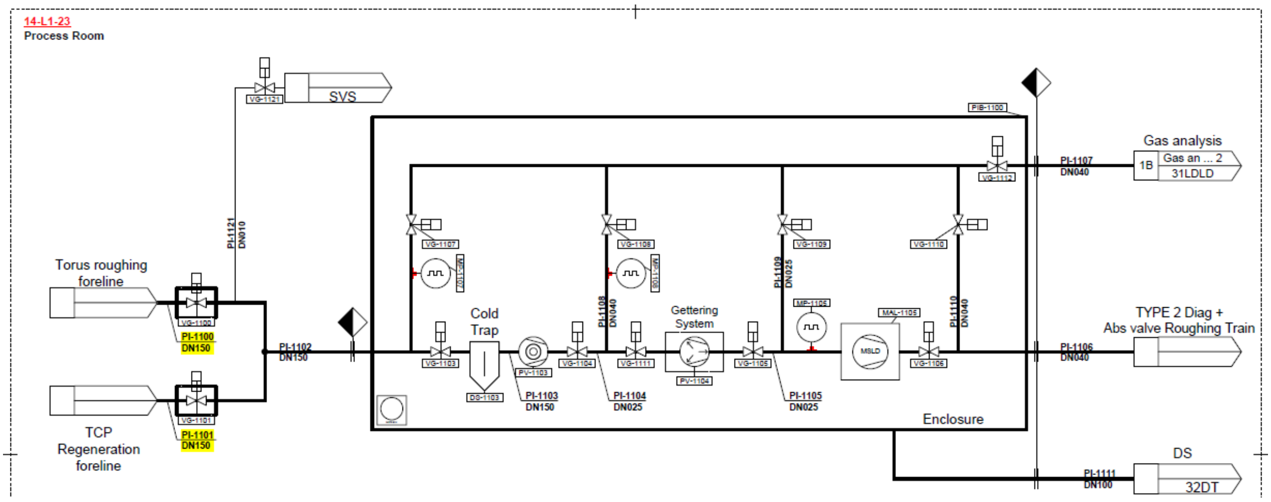

Figure 5 - Torus remote leak detection station PID

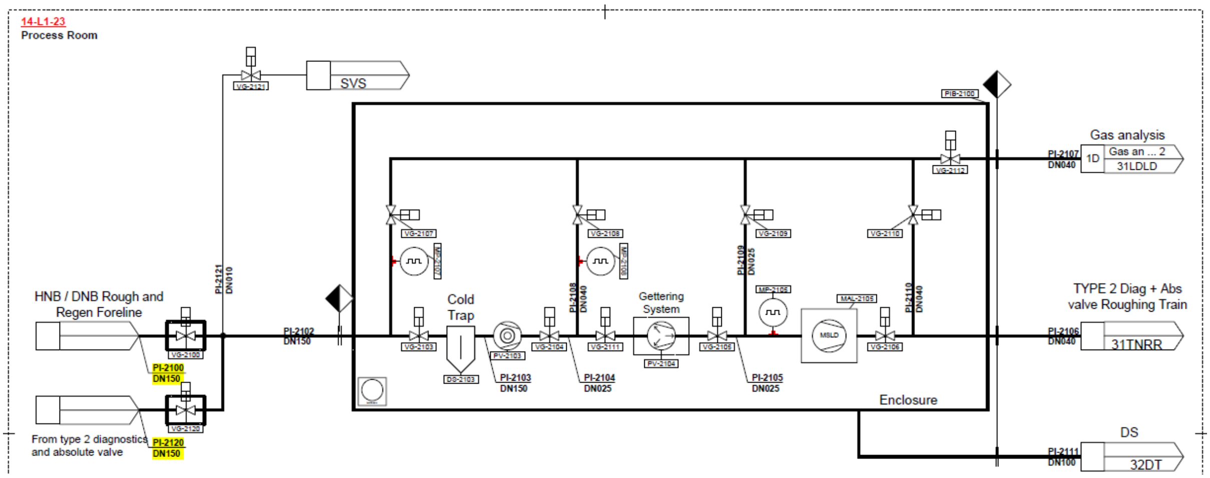

Figure 6 - NB remote leak detection station PID

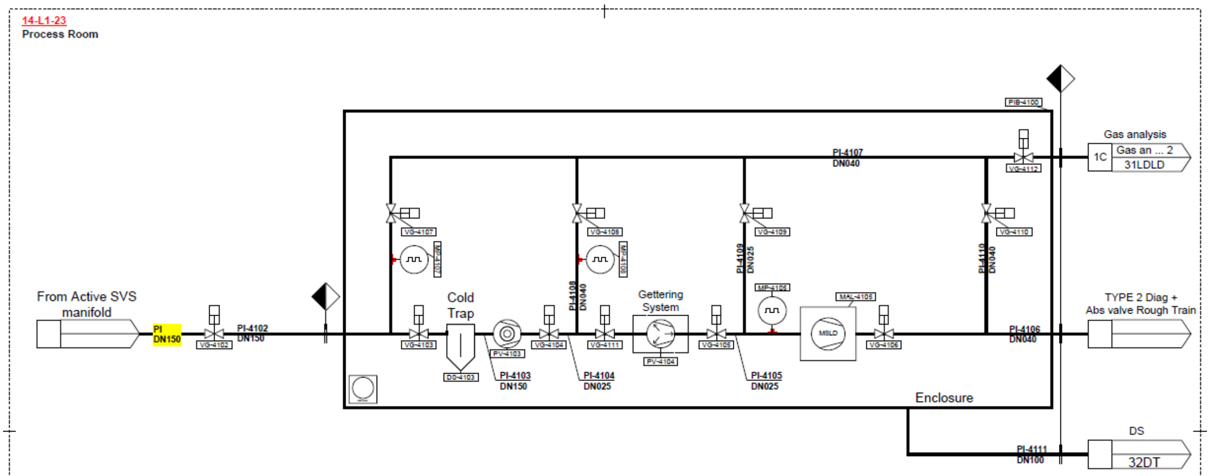

Figure 7 - Active Service Vacuum System (SVS) remote leak detection station PID

3. Calibration system description

The Calibration station provides gases at defined flow rates to the primary vacuum system(s). The gas supplied in this way is required for the calibration of the Primary Vacuum Systems Leak Detection and Water Leak Localization System.

Gas Type	Flow rate (Pa.m^3.s^{-1})	Accuracy
Water mixture	Flow rates between 10^{-6} 10^{-3}	±1 % of nominal flow
Air mixture		
Helium		
Neon		
Deuterium		
Argon		
Nitrogen		

Table 3. Calibration station performance

The calibration station consists of 3 local gas bottles connectable trough the opening of valves to an orifice. Gas flows from the bottle through the orifice and into the main vacuum vessel. The flow of gas through the orifice is controlled by remotely operated needle valves in series with the gas stream. The orifice is approximately of 50 µm diameter through a 50 µm thick stainless steel foil. The calculated helium flow through the orifice (at ΔP=0.1 MPa, ambient temperature) is 1×10^{-5} Pa.m^3·s^{-1}. In addition to the orifice the user may select that the calibration gas flows to the main chamber through a remotely operated needle valve. The calibration station is located together with Torus direct leak detection station in HNB2.

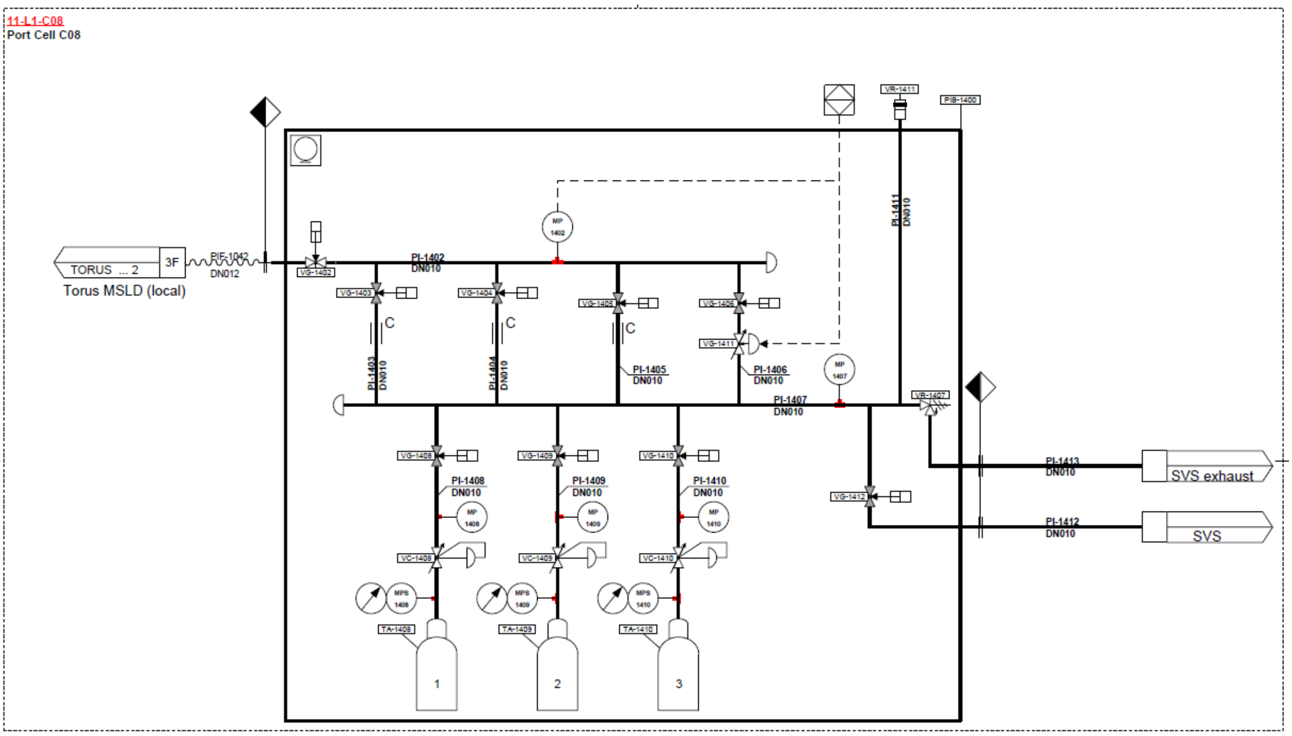

Figure 8 – Gas calibration system PID

The needle valve for the calibration station shall be all-metal variable leak valve, parameters of which are presented in the Table 4.

Parameter	Value
Adjustable gas flow	1×10^{-11} Pa.m^3.s^{-1} to 10^{-5} Pa.m^3.s^{-1}
Differential pressure at opening	≤ 10^6 Pa
Pressure range	UHV to 10^6 Pa
Leak rate: valve body, valve seat	<1×10^{-11} Pa.m^3.s^{-1}

Table 4 - Reference model of needle valve parameters

4. Gas analysis station

The Gas analysis station (Fig.9) is located in the vacuum pumping room and comprises instrumentation required to analyze gasses pumped from the active clients via remote leak detection stations of Torus vacuum, Neutral Beam and active SVS (Service Vacuum Systems). The gas analysis station instrumentation and its function are listed in the Table 5.

Instrument	Function
Micro Gas Chromatograph (mGC)	Gas analysis (at elevated pressure)
Ionization Chamber	Tritium measurement
Differentially pumped RGA	Gas analysis

Table 5 - Gas analysis station instrumentation.

The Gas enables compositional analysis and activity measurement of a gas sample. These gas samples may arise from initial evacuation of a volume or from regeneration of a cryopump that has been pumping a volume.

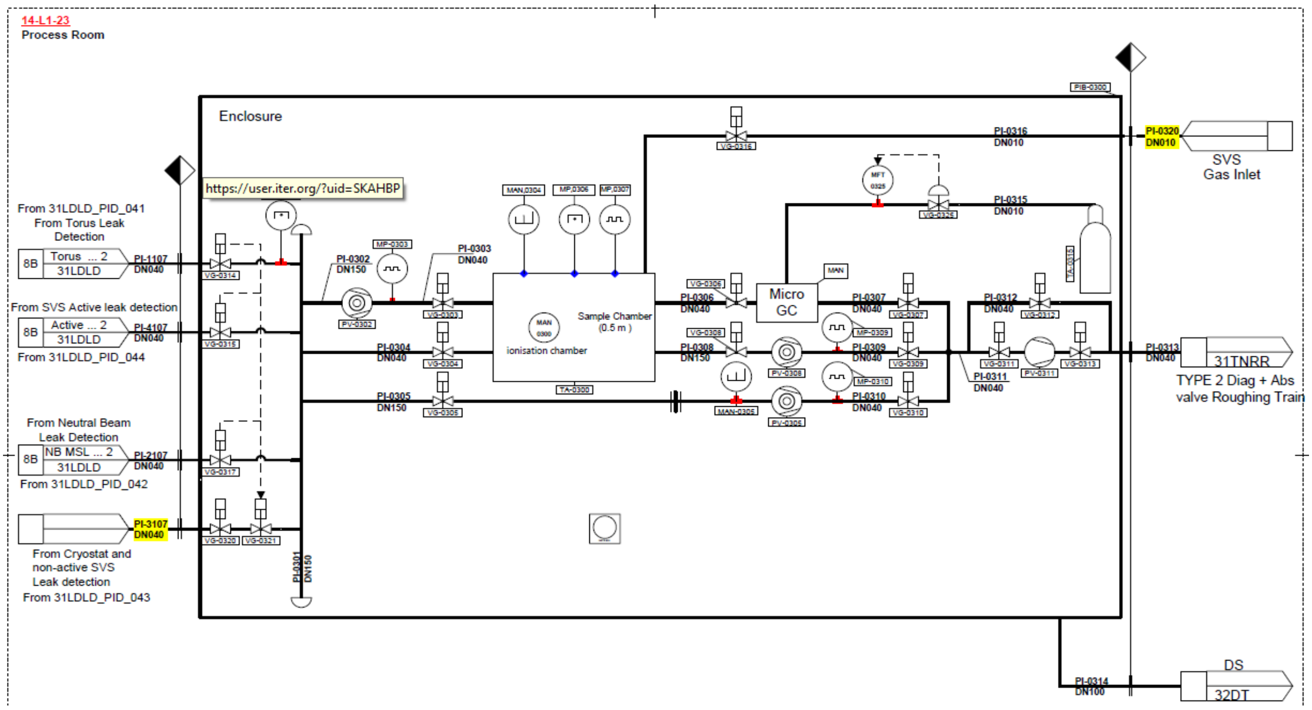

Figure 9 – Gas analysis system PID

5. Leak detection system for Cryostat.

Cryostat leak detection stations are located in the room 24 of tritium building which is shown in Figure 10. Main components of the remote leak detection stations are the same as the any other remote LD system for Torus Vacuum or Neutral Beam. Leak detection stations of potentially active clients will be located within individual enclosures as an extra confinement barrier since getter maintenance involves disconnection and replacement of cartridge and also a changing of instrumentation is required during operation and maintenance periods. Enclosures are connected via common manifold to single point connection to the Detritiation System (DS) in vacuum pumping room.

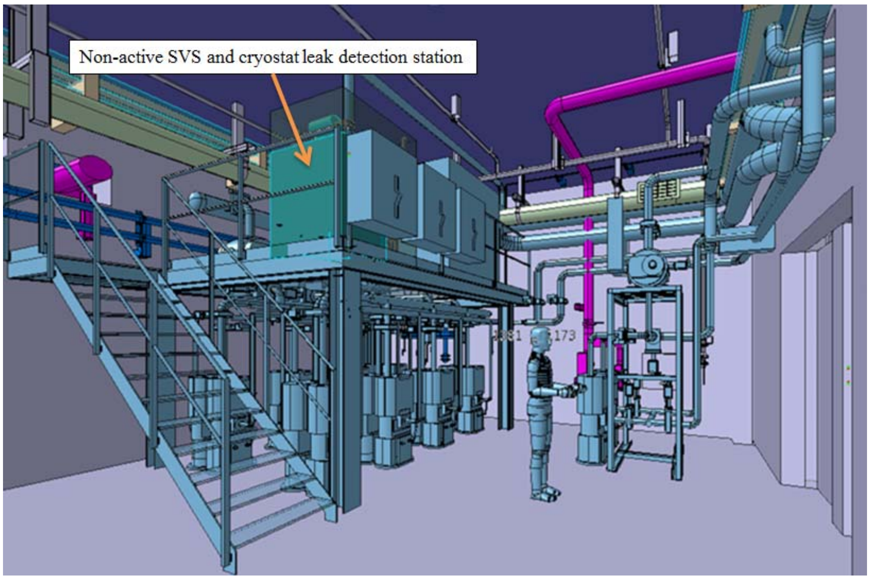

Fig. 10 Location of remote non-active SVS and remote cryostat leak detection station in the room 24 of VPR

Regarding the design of the Direct Leak detection system for the Cryostat is still under development; CDR will take place in December 2018. First conceptual design has been based in the following components:

- DN300 ITER Flange double contained bellows
- 8 All metal gate valves DN250CF
- Collector OD 300mm with ports
- MSLD module

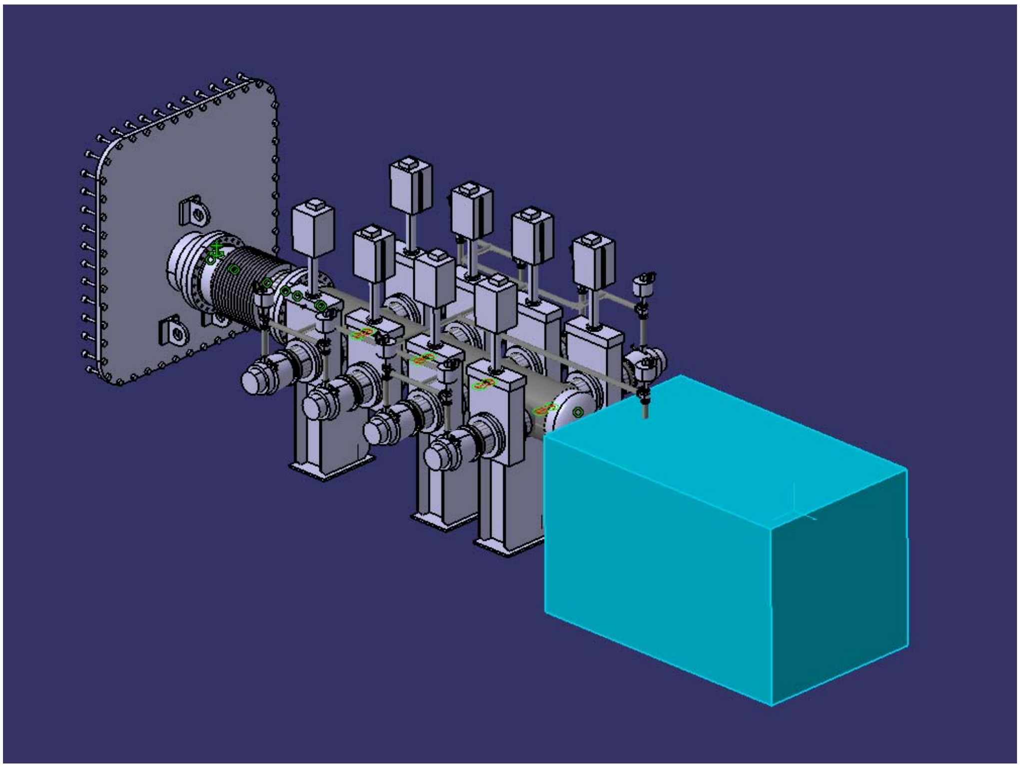

Figure 11 - Concept layout of each leak detection station set up for Cryostat Direct LDS.

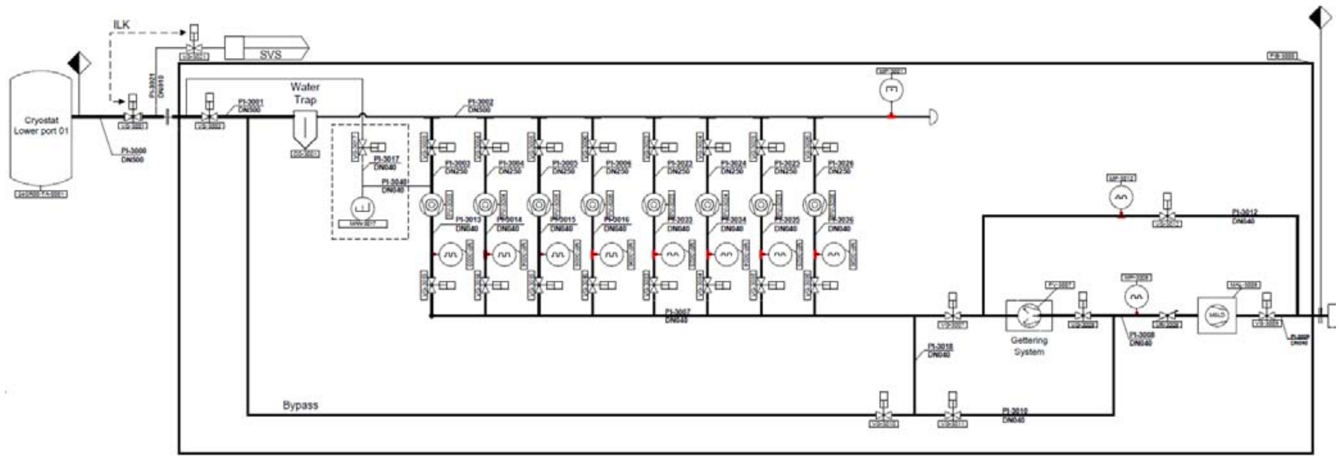

Figure 12 – PID for the Cryostat LD system

2.3.2. Subcomponents

Currently primary leak detection and localization system is being defined at the Conceptual design stage; this section to be updated after PDR is completed. Anyway, components like flanges, valves, pipes, etc. shall be standardized wherever is feasible. A brief description of the subcomponents is given below:

Pipe supports and frames

Pipe supports and frames shall be designed according the Load specification at each location.

https://user.iter.org/?uid=PLCN5F (Vacuum pumping room for the remote systems) [2]

https://user.iter.org/?uid=PJLYL2 (Torus local LDS) [3]

https://user.iter.org/?uid=V3B4CB (Neutral Beam Direct local LDS) [4]

And interface points with buildings will be defined at the PDR stage.

Vacuum Piping

The vacuum piping shall be made of austenitic stainless steel 1.4307 304L or/and 316 SML (seamless).

Co = max 0.05%

Nb = max 0.10%

Ta = max 0.0%

Weld filler: Co

Pipe sizes range from DN40 to DN500. Some of these pipes are PIC (nuclear Protection Important Components following the French Order of 2012). They should be designed and manufactured according to ASME B31.3 Cat M fluid.

A heating system should be provided to perform bake out up to 200°C.

Valves

The LD&LC system will be equipped with the following rough number of valves:

- 1 All metal gate valves (DN320)
- 17 All metal gate valves (DN250)
- 2 All metal gate valves (DN320)
- 8 All metal gate valves (DN150)
- 54 isolation valves (DN40); 15 isolation valves (DN25) and 10 isolation valves (DN10)

The material for all valves is stainless steel 1.4404 or 1.4435 (316L) for the complete valve, including stem and bellows. They should be actuated by spring loaded pneumatic actuators.

Valves shall be of all metal construction with all metal confinement boundary and metal seals.

The isolation valve between the connecting duct and pumping manifold shall have double confinement with the interspace connected to the SVS.

The isolation valves between the pumping manifold and the TMPs shall have double confinement with the interspace connected to the SVS.

Valves are already been qualified by IO under strategic agreement, if those valves are not procured from this contract, a qualification by experiment under the load conditions as specified in Section 2.3.2. shall be performed to guarantee the safety function of confinement.

Relief devices

There shall be relief devices which protects the different vacuum systems connected either to the torus vacuum or the NB vacuum or Cryostat vacuum from sudden overpressure. The different thresholds should be defined at the PDR stage.

Instrumentation and control

The following vacuum instrumentation should be procured for the different subsystems, roughly these are the figures according to the current design status on the overall number of instrumentation:

- 20 Pirani gauges (10-3 mbar to Atmospheric pressure) in DN40CF Flange
- 20 Cold cathode gauges (10-9 mbar to 10-6 mbar) in DN40CF Flange
- 10 RGA (0 -100 A.M.U) DN40CF Flange
- 8 Mass spectrometers

These vacuum instrumentations, the actuators of the gate valves and the control supplied to the electrical motors of the turbomolecular pumps should be controlled by a centralized system and should be able to be integrated into the **CODAC system**.

Two of these cubicles are classified as PIC. The junction boxes and the cabling to connect the instruments to their controllers should also be included.

MSLD modules

A total of 8 Mass Spectrometer Leak Detection units need to be procured for the LD&LC systems.

The scope will include the design (a conceptual design model will be provided as input data to be developed to final design and manufacturing level); procurement; manufacturing; assembly; factory acceptance testing; and shipment of four MSLD modules to the ITER site in France.

Figure 13 below shows a concept of each Mass Spectrometer Leak detection stations, consisting in:

- A Water pumping device (cold trap)
- A Hydrogen selective pumping device (getter pump)
- Magnetic Sector Mass Spectrometer (MSLD)
- Isolation valves all metal, piping, supports to fit with building interfaces.

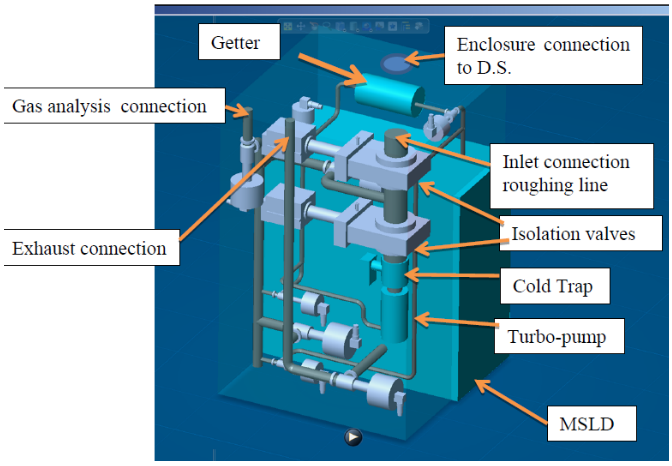

Figure 13 - Concept layout of each leak detection station

The overall dimensions for each leak detection station due to space reservation should not exceed 2 m by 1,5 m wide and 2 m in height.

The components of each system will be mounted in a dedicated framework which will interface with the floor in the respective location.

Each system will have an inlet connection to its respective pumping system foreline, an exhaust connection back to the respective pumping line and a connection to the Gas Analysis module.

Around frameworks containing MSLD systems (Torus vacuum, NB and SVS remote LDS) will be formed an enclosure that will be connected to detritiation system (D.S.) via rigid pipework incorporating a bellows section.

Magnetic Sector Leak Detector

The MSLD (Magnetic Sector Leak Detector) shall utilise 180° magnetic deflection mass spectrometry for the detection of helium.

It shall be possible to remotely vary the conductance of the inlet to the MSLD from 100% (DN 40 nominal flow) to 10 % of nominal flow in ≤ 5 s.

The MSLD shall have a minimum detectable leak rate for helium ≤ 1 x 10^{-11} $Pa.m^3.s^{-1}$.

The MSLD ion source shall have a minimum of two filaments. The filaments shall be protected from damage due to adverse vacuum conditions (rapid venting). Switching between filaments (on failure) shall be automatic.

The MSLD amplifier drift shall be less than 2% of the full scale on the most sensitive range and the noise level shall be less than 2% of the full scale peak to peak.

The MSLD response time to helium at the unit inlet at a partial pressure of 10^{-7} Pa shall be less than 1 s.

The MSLD amplifier shall have a function for zero offsetting by at least two orders of magnitude.

The MSLD unit of measure shall include but not be limited to $Pa.m^3.s^{-1}$.

Residual Gas Analyzer (RGA)

The RGA shall be capable of measuring the atomic mass of gas species from 1 to 100 A.M.U at a mass resolution of better than 10% valley for peaks of equal height across mass range.

The RGA shall utilise Faraday cup and electron multiplier detectors.

The RGA shall utilize a closed ion source for higher pressure operation.

The RGA shall have a minimum detectable partial pressure sensitivity of $< 1.5 \times 10^{-11}$ Pa.

The RGA ion source shall have a minimum of two thoria coated iridium filaments. The filaments shall be protected from damage due to adverse vacuum conditions (rapid venting) or switching on at atmospheric pressure. Switching between filaments (on failure) shall be automatic or via remote control.

It shall be possible to isolate the RGA from the connecting duct through the remote closure of a valve.

There shall be an orifice to limit the gas flow between the system pumping duct and RGA.

It shall be possible to pump between the orifice and the analyser, in such a way that with the VV or NB at atmosphere pressure, the vacuum space between the orifice and the analyser pressure shall be below 10^{-6} Pa.

It shall be possible to bake the connection, including isolation valve, between the RGA and the system pumping manifold.

Vacuum joints

All vacuum joints shall utilise metal seals and be in compliance with the ITER Vacuum Handbook **Error! Reference source not found.**.

Vacuum joints shall be supplied with seals/gaskets.

Connections to the SVS shall utilise 6mm (1/4 in) VCR male fittings.

2.4. Instrumentation and Control

2.4.1. Scope

The procurement of all cables, connectors, cubicles and components to connect the instrumentation and control devices of the above-mentioned systems are included in the scope of the LD&LC. These components will be delivered fully factory acceptance tested by the supplier.

The scope will also include the cable and connector selection, cable routing, selection of all other components, general layout and distribution of components considering distances and sensor and actuator technology as part of the final design. Analyses have to be performed to show structural integrity of the cubicles in seismic and transport loads.

Installation and on-site testing is outside of the scope.

2.4.2. Operation

The components will be mainly located in the port cells of ITER, which are subject to magnetic fields and ionizing radiation. Validated materials and off-the-shelf components will be proposed which withstand these environmental conditions. Qualification tests may be required for PIC components.

2.4.3. Description

Each LD&LC system will require one floor-standing I&C cubicles and one wall mounted I&C cubicles.

All cubicles will include all internal wiring and I&C equipment. The scope includes all cables, fibres, pipes and connectors required to connect these cubicles to the rest of the system.

The I&C for this system is specific of vacuum application. The types of sensors and controllers are described in the Instrumentation and Control under Section 2.1.3 at the subcomponents level.

For each LD&LC system it is estimated that there will be 75 analogic and 50 digital signals. (The total amount of signals for the system would be 1000 analogic and 750 digital.).

2.5. Control software

2.5.1. Scope

The software package to control all the instrumentation of the LD&LC shall be delivered. This includes process software and integration software.

2.5.2. Description

Process software is based on industrial PLC, such as Siemens step 7.

Integration software is based on ITER specific control system framework (CODAC Core System, CCS) based on EPICS and running on Red Hat Linux.

3. Quality assurance requirements

As specified above, the components of the LD&LS are high quality class components, including some Protection Important Components (nuclear safety related components).

All activities have to follow a dedicated Quality Plan and detailed Manufacturing and Inspection Plans, which identify surveillance points for each activity to ensure that the requirements are met. The supplier has to ensure that each of its subcontractors applies the same quality requirements.

Specifically for PIC sub-components, certain additional quality controls and qualification tasks are required, for example: independent verification of critical activities, follow-up and demonstration of requirements, surveillance of critical tasks by the ITER operator, qualification of equipment under the most stringent design conditions, etc.

To be more precise, there will be 3 main qualification to carry out.

1) Qualification of every system under the specific load cases to guarantee the confinement function (safety or defined requirement)
2) Qualification of the RGA with the cables to withstand the required environmental conditions.
3) Qualification of the MSLD with the cables to withstand the required environmental conditions.

	TDLDS & Leak Calibration	NBDLDS	Remote LDS	Cryostat Direct LDS	Gas analysis system
Location	11-L1-PC08	11-L3-01 HV	14-L1-23 Vacuum pumping room	11-B1-C01	14-L1-23 Vacuum pumping room
Radiation dose	8.3 e4 Gy	2.7 e4 Gy	<1 Gy	4 e5 Gy	<1 Gy
Magnetic field modulus vertical direction	N/A	N/A	15 mT	N/A	15mT

Table 5. Environmental conditions for each leak detection system

4. F4E MARKET SURVEY

To establish an optimum contract strategy, F4E needs to develop its understanding of the market with a comprehensive list of possible EU suppliers interested in the procurement of the LD&LC systems.

In the frame of the market survey, interested suppliers are invited to submit information by filling in the questionnaire in the following link:

https://www.surveymonkey.com/r/HD7MSY7

This information will be used by F4E and IO and will not be communicated to other parties.

Reference Documents:

[1] ITER_D_2EZ9UM v2.3 - ITER Vacuum Handbook and Appendices
[2] ITER_D_UC3NDU v2.3 - System Load Specification for systems in the Vacuum Pumping Room (VPR)
[3] ITER_D_PJLYL2 v2.5 - System Load Specification for the Torus Direct (Local) Leak Detection system
[4] ITER_D_V3B4CV v1.3 - System Load Specification for the Neutral Beam (Local) Leak Detection system