Vacuum Technology for ITER

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Abstract

The vacuum systems for ITER are characterized by the requirements for tritium compatibility, tolerance of high magnetic and radiation fields and remote maintainability. In addition, although the vacuum levels are relatively modest, high pumping speeds are needed to achieve the high gas throughputs required. The design solutions adopted, the status of the development programme and the issues still to be addressed before commitment of the designs to fabrication are described in the paper.

1. Introduction

The ITER fusion machine to be built at Cadarache, France requires the development of novel vacuum technologies for the cryopumping systems for the torus, neutral beam injectors and cryostat, mechanical rough pumping systems, and for leak detection and localization. The presence - actual or potential - of tritiated gas species exerts a strong influence on the technologies which can be deployed in ITER vacuum systems. The outgassing rates from plasma facing components and the gas species evolved are strongly dependent on the selection of plasma facing materials; the present design of ITER includes beryllium, tungsten and carbon fibre composites. The cryopump programme, ongoing at FZK for the last 20 years, covers all aspects of the development, from investigation of candidate pumping concepts through characterization of small scale cryopanel coupons to testing of a full scale ITER prototype Torus Exhaust Cryopump, which is presently being fabricated. Designs of the cryopumps for the ITER vacuum systems have been standardized to the greatest extent practical. A focussed programme to develop a robust, tritium-compatible cryosorption panel concept has been carried out and a technical facility for coating panels with calibrated thin layers of activated charcoal sorbent has been built and used in the production of cryopanels for ITER and other fusion cryopumping applications.

Mechanical roughing is by a set of pump trains which include specially adapted Roots pumps with enhanced internal and external leak tightness. The latter is essential to preclude cross-contamination between the tritiated process gases and the lubrication oil of the timing gears. A reduced scale pump equipped with ferrofluidic shaft seals between the process gas and gear compartments has been successfully tested. Scale-up studies indicate that the concept can be used at ITER-relevant capacities, but experimental validation remains to be done.

The development of the ITER-specific vacuum technologies and the resulting system designs are described in the paper and critical issues still to be resolved in the ongoing R&D programme identified.

1.1 ITER objectives

Planned to start operation in 2016, the International Thermonuclear Experimental Reactor (ITER) is a key project on the path to demonstrate that nuclear fusion is a viable source of energy. The role of ITER includes demonstration of the technological feasibility of fusion (availability) and testing of fusion power plant technologies and safety features (tritium) on a scale unprecedented on present day fusion devices.

1.2 Scale up JET to ITER

The largest existing fusion machine is JET, at Culham, UK. While the ITER torus base pressures are similar to JET, the ITER pumping duties are significantly more demanding
because the torus volume is approximately 10 times larger and ITER plasma shots will be up to 400s. (short pulse operation) and up to 3000s. in long pulse mode, compared with a few seconds for JET. The tritium throughput during the main DT campaign (DTE) in 1997 in JET was roughly equivalent to one day of planned ITER DT operation.

1.3 Pumping requirements
There are several interconnected Vacuum Pumping Systems in ITER. The principal systems are the Torus Pumping, Neutral Beam Cryopanel and Cryostat Pumping systems, which are based on cryopumping, and the Rough Pumping, Pellet Injector Pumping and Service Vacuum systems, which are composed mainly of mechanical pumps. Design concepts for these have been developed according to the following guidelines:
- Vacuum pumping systems are based to maximum extent on common components;
- Cryopumps are cooled by supercritical helium at ~4.5K from a supply which is integrated with the ITER superconducting magnets;
- Cryopumping system regeneration schemes (at different temperatures in the range 80-475K for the different gas species) are based on sequential regeneration of individual pumps to:-
  - minimise gas inventories (hydrogens, including tritium) and
  - smooth demands on cryodistribution system.
- Torus exhaust and cryostat pumps have same configuration;
- NBI cryopanels are similar to torus exhaust and cryostat pump panels;
- The four (mechanical) roughing pump sets are identical, to maximise redundancy and minimise cost;
- Most ITER vacuum pumping systems have to be designed for tritium compatibility.

3. Cryopumping System development
The design of ITER vacuum cryopumping systems and of the pumps has focused primarily on the Torus Exhaust system, with the other systems following the same design principles and embodying standardized components wherever possible. The main features of each system are outlined below.

3.1 Torus Exhaust
This system carries out the following functions:
- Roughing of the torus from atmosphere pressure;
- Purging of the vessel prior to remote maintenance;
- High vacuum pumping of the torus during all phases of operation, including plasma operation, tritium recovery from PFC’s, conditioning and leak detection.

The main parameters for these operations are given in table 1

| Table 1: Torus pumping system parameters |
|-----------------------------------------|
| **Parameters**                          | **Unit** | **Value** |
| Vacuum Vessel free volume              | m$^3$    | ~2000     |
| Time for pump down from 10$^5$ Pa (1 bar) to 50 Pa by roughing system | h        | <=60      |
| Total surface area for outgassing      | m$^2$    | ~2600     |
| Base pressure for hydrogen isotopes/impurity gases | Pa | <10$^{-5}$/10$^{-7}$ |
| Time to pump down to base pressure     | h        | ~100      |

*Plasma Operations*
Typical divertor pressure during plasma operations \( \text{Pa} \) 1-10
Maximum throughput during plasma operations \( \text{Pa.m}^3/\text{s} \) 153
Minimum He pumping speed during plasma operations \( \text{m}^3/\text{s} \) 30-40

3.1.1 Divertor Conductance studies. A significant obstacle in providing sufficient pumping speed at the torus is the low conductance of the divertor and pumping duct system. Modelling of the flow through the complex divertor geometry is complicated by the fact that the flow conditions are in transition regime where comparison of existing models exhibit some discrepancies. The ITERVAC code has been developed to investigate this critical regime and the results of analyses of the system conductance will be benchmarked against experimental data to be obtained from the ITERVAC test loop which has just been completed at FZK [1].

Eight pumps are connected to four pumping ports, each port with one “in-line” and one “branched” pump.

3.1.2 Cryopump Development Programme (Torus Exhaust)

- Cryosorption panels
  More than 400 cryosorption specimens (50 mm diam.) were prepared using:
  - Sorbents: activated carbons, molecular sieves, sintered metal, porous ceramics, metal fibre fleece;
  - Bondings: solders, plasma sprayed layers, inorganic cements, mechanical techniques;
  - Substrates: copper, aluminium, stainless steel. A spraying technique was developed for the coating of large surfaces with cryosorption layers.

  As a result of these tests, activated charcoals bonded by cement and braze and molecular sieves bonded by cement were chosen for the fabrication of 430 mm dia panels for the next stage of development in which approximately ten liquid helium cooled cryosorption panels (including one based on argon cryotrapping) with a diameter of 430 mm. were tested in a vertical vacuum vessel. The cement adopted is a commercially available, proprietary two-component product which has been extensively tested in metal to charcoal bonding applications. Resulting from these tests the cryosorption panel system described in table 2 was adopted for all main cryopumping systems in ITER. A facility for application of calibrated thin layers of bonding agent and sorbent to panel substrate has been constructed at FZK.

| Component       | Material                                                                 |
|-----------------|--------------------------------------------------------------------------|
| Substrate       | Stainless Steel, SS 316 L (~1.5-2.0 mm thick)                            |
| Bonding agent   | Two component inorganic cement                                           |
| Sorbent         | Granular coconut shell activated charcoal, Size 12-30 US-mesh, (1.2 mm), |
|                 | BET* surface 1100-1200 m²/g, microporous (maximum at 1.0-1.2 nm pore width) |

* BET: Brunauer, S., Emmett, P.H., Teller, E., index

Following the panel development programme, a model pump with 4m² of cryosorption surface, approximately 50% of the (then) ITER torus exhaust pump area was designed, fabricated and installed in the TIMO test facility at FZK for an extensive campaign of performance, mechanical and safety tests, as described in [2]. The campaign, which extended over several years included the following parameters: -
Performance tests (pumping speed, capacity, impurity (poisoning) and Regeneration tests)
- Safety tests (sudden venting)
- Mechanical tests (cycling tests and post operational inspection)

Tritium compatibility was demonstrated in separate tests of a representative cryopanel at JET. Pumping of tokamak exhaust gas was successfully completed; post-service inspection, including residual tritium measurements, are in progress.

EFDA in collaboration with FZK and EU industry is presently building a full scale Prototype Torus Cryopump (PTC) [3]. Although the model pump tests were highly successful, it was considered prudent to test a full scale pump because:
- Ten almost identical (8 torus exhaust and 2 cryostat) pumps are needed, plus NBI cryopanels which use similar panel construction. Thus any required design adjustments should be identified before commitment of fabrication of multiple pumps;
- Pumping duties are not a straightforward scale-up from the model pump;
- Dimensional constraints from remote handling, VV extension duct cross-section accounted for in PTC design;
- Some critical mechanical components (double bellows compensator, etc.) were not investigated in the model pump;
- Some features of the model pump which were problematic (water cooling and alignment springs of valve disc, shaft bearing arrangement, etc.) have been changed/reviewed for PTC.

The PTC design differs from the ITER series torus exhaust cryopumps in a few minor details to facilitate its accommodation in the existing TIMO test vessel, but these differences will not compromise the relevance of the test results. The target helium pumping speed of the PTC is 40 m³/s.

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4. NBI Panels

ITER will be provided with two (optionally three) heating and one diagnostic Neutral Beam Injectors located on the equatorial plane of the tokamak. These injectors are pumped by large cryosorption panels of the same basic configuration as the torus exhaust pumps. The current design has flat, vertical panel arrays arranged on the sides of the NBI boxes, to permit vertical removal of components for maintenance. The next development step will be the construction of
a Neutral Beam Test Facility to be hosted by Consorzio RFX in Padua, Italy. The basic configuration of the panels is shown in Figure 2.

![Figure 2: Neutral beam Cryopanel Outline](image)

5. Cryostat Pumps
The cryostat pumps [4] fulfil the following functions:

- dehydration of the cryostat internals prior to magnet cool-down;
- evacuation of cryostat to high vacuum prior to magnet cool-down;
- pumping of helium leaks from magnet cooling circuits;
- pumping of protium from long term outgassing from warm in-cryostat metallic surfaces;
- pumping and detection of external air leaks to reduce ozone hazard;
- pumping of gases generated by irradiation of exposed epoxy (e.g. methane, ethane, water).

The panel arrays and inlet valve/actuators of the two cryostat cryopump will be identical to torus cryopump. However, as these pumps are installed in the cryostat volume rather than ducts (as in the case of the torus pumps) they will embody a casing to provide inlet valve seat and private regeneration volume, which can be pumped out by the roughing system.

6. Roughing pumps
The main functions of the rough pumping system include:-

- regeneration of Torus Cryopumps (highly tritiated);
- regeneration of NBI Cryopanels (moderately tritiated);
- roughing of Service Vacuum System (slightly tritiated);
- regeneration of Cryostat Cryopumps (non/slightly tritiated);

All four trains are identical for maximum flexibility, and must therefore all be tritium-compatible.

The pump trains, which will consist of suitably modified pumps such as Roots blowers, screw, scroll and metal bellows pumps, must discharge to processing systems (Tritium Plant, Vent/Atmosphere detritiation, Release point) appropriate to the tritium concentration in the gas streams being pumped. Complex manifolding and changeover valves are foreseen to facilitate these operations, and procedures for purging sections of the system to prevent cross-contamination between campaigns when they have handled gases with different tritium concentrations.

A key feature of the proposed roughing pump concept is ferrofluidic shaft sealing between pumped gas compartment and oil lubricated timing
Figure 3: Ferrofluidic Seal Configuration

gear compartment to prevent migration of oil to the downstream piping and processing systems and contamination of the pump oil with tritium, which would degrade lubrication properties and give rise to a tritiated waste stream. Tests of a 250 m³/h Roots pump have validated the shaft sealing concept and leak rate determination in a tritium test loop is in progress. This will be followed by the scale up of the pump designs to cover the full range of pumping speeds needed in the ITER roughing system, which are likely to be in the range of 6000 m³/h [5].

In the pellet injection system the scheme for recovery of propellant gas includes Roots and screw pumps, with capacities broadly in line with roughing pumps. As the gases handled will be tritiated, similar upgrading of standard pumps to that proposed for the main roughing pumps are envisaged.

7. Leak detection and localization

Early leak detection and precise leak localization are essential to maximization of machine availability. Localization of water leaks to the level of individual in-vessel components is challenging due to the large number of first wall modules and divertor cassettes. The detection and localization of air leaks, which will in many cases be associated with vacuum vessel ports or penetrations for plasma heating and diagnostic devices is complicated by the diversity of these systems. A sequence of procedures for leak localization is foreseen. Following detection of an in-vessel water leak, it is proposed to add tracers to cooling water circuits and then individual cooling water loops. The tracers will be exhausted from the machine by the Torus Exhaust Cryopumps and the regeneration stream will be analysed for their presence. The low concentration of tracers expected from typical leaks complicates their detection. This step will be followed by the deployment of an in-vessel remotely operated detection device to traverse the plasma-facing components and pinpoint the location of the leak; the details of this procedure remain to be determined, but development of hardware such as a remote manipulator capable of deploying a sniffing device inside the vessel under vacuum is under way [6]. Following leak localization faulty/suspect components will normally be taken to the Hot Cell for repair; details of the procedures will be dependent on the exact location, size and nature of the leak, and remain to be determined.

8. Conclusions

The development programme for cryopumps, focused on the torus exhaust pumps. Tests of the 50% scale model pump have extensively qualified the design of all ITER cryopumping applications by validating a broad range of representative operating conditions. Some mechanical features, such as the double bellows arrangement on the valve stem, remain to be validated on the PTC presently being fabricated.
Adaptation of Roots pump concept for tritium compatibility was demonstrated with a small scale (250 m3/h) pump. Larger scale Roots pumps and other types need to be investigated, but it is confidently expected that scaling will be feasible within the range of pumping speeds required. Strategies for management of high moisture content gases in the roughing train will be addressed in the planned development programme.

Strategies for leak detection and localization have been outlined and work on validation of the proposed techniques is under way.

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