Validated Design of the ITER Main Vacuum Pumping Systems

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Abstract. Forschungszentrum Karlsruhe is developing the ITER high vacuum cryogenic pumping systems (torus, cryostat, NBI) as well as the corresponding mechanical roughing pump trains. All force-cooled big cryopumps incorporate similar design of charcoal coated cryopanels cooled to 5 K with supercritical helium. A model of the torus exhaust cryopump was comprehensively characterised in the TIMO testbed at Forschungszentrum. This paper discusses the vacuum performance results of the model pump and outlines how these data were incorporated in a sound design of the whole ITER torus exhaust pumping system. To do this, the dedicated software package ITERVAC was developed which is able to describe gas flow in viscous, transitional and molecular flow regimes as needed for the gas coming through the divertor slots and along the pump ducts into the cryopumps. The entrance section between the divertor cassettes and each pumping duct was identified to be the bottleneck of the gas flow. The interrelation of achievable throughputs as a function of the divertor pressure and the cryopump pumping speed is discussed. The system design is completed by assessment of the NBI cryopump system and integrating performance curves for the roughing pump trains needed during the regeneration phases of the cryopumps.

1. Introduction

ITER combines three high vacuum pumping systems for evacuation and maintenance of the required pressure levels in the torus (1350 m³), the cryostat (8400 m³), and the neutral beam injectors (570 m³). The torus primary pumping system is not only designed to pump the exhaust gases from the plasma, but is also needed during fine leak-testing of the torus, for wall conditioning and bake-out and to provide ultimate vacuum in the torus [1]. This means that a broad spectrum of gases, such as all the isotopic hydrogen species, noble gases and low- and high-molecular impurities (air-likes, water, hydrocarbons) will have to be pumped at variable throughputs, ranging from very small to very high. Control of the gas throughput, especially the helium ash produced by D-T fusion reactions, is one of the key issues affecting the performance and achievable burn time of a fusion reactor.

All high vacuum pumping systems on ITER are based on cryopanels forced-cooled by 5 K supercritical helium. To guarantee for sufficient helium and protium pumping, the cryopumps are based on cryosorption (sorption for light and re-sublimation for heavier gases) by using cryopanels in quilted design, which are coated with activated charcoal as sorbent material. This design feature is common to all three primary pumping systems, see Table I. Extensive preparatory tests were run in the past to find an optimum combination of sorbent type and bonding cement, resulting in a ~ 1 mm thick layer of specific granular activated charcoal, bonded by an inorganic tritium-compatible cement. Based on this optimum panel set-up, an essential qualification programme has been performed at Forschungszentrum Karlsruhe (FZK) to determine the performance characteristics and to assess the suitability and effectiveness of the quilted cryosorption panel design [2]. The test panels are coated using a special spray technique developed at FZK.

TABLE I: MAIN PARAMETERS OF ITER PRIMARY PUMPING SYSTEMS [1].*)

	Torus	NBI	Cryostat
# Pumps	8	2(3) (Heating) +1 (Diagnostic)	2
Main Pumping Mode	Dynamic = maintain the pressure at a total gas throughput of: (120 Pa·m³/s (fuelling rate) or 60 Pa·m³/s (He case))+ (33 Pa·m³/s (impurities)); Base pressure for hydrogen isotopes: 10^{-5} Pa.	Dynamic = maintain the pressure at a throughput of 36 Pa·m³/s (of protium per Heating-NBI)	Transient pump-down to 10^{-4} Pa and steady-state pumping of magnet coolant leak helium
Gases	Hydrogens (all isotopes), helium, impurities.	Hydrogens (H_2, D_2)	Nitrogen/Air, outgassing gas
Sorbent coating	Yes	Yes	Yes

*) Throughputs and flow rates always refer to 273.15 K.

2. The Torus Exhaust Primary Pumping System

2.1. Pump Assessment: Experimental (TIMO) and Simulation (MOVAK3D)

During plasma operation, the ITER torus is pumped by eight torus cryopumps which are located in four divertor ducts (two pumps per duct, one branched and one in-line) to pump the exhaust gas (see FIG. 1). They are characterised by an integral inlet valve which can be fully closed to perform regeneration, and partially closed to throttle the torus exhaust gas flow to keep the pressures in the divertor private flux region between 1 and 10 Pa (ITER design requirement [1]), see FIG. 2.
The tritium inventory of all torus cryopumps open to the torus volume is subject to an administrative safety limit of 120 g. Another operational safety constraint is that the total hydrogenic inventory of an individual cryopump shall be less than 3g/m³, which, following deflagration, results in a pressure of 0.2 MPa, the design pressure of the ITER vacuum vessel and appendages. During long pulse DT plasma discharges, the cryopumps have to be regenerated on-line to keep the hydrogenic gases within these limits. This is done using a staggered operation pattern in which at any instant 4 of the pumps (two branched and two direct) are pumping and the remaining four are in regeneration [3]. The reference ITER staggering interval of 150 s (which implies a cycle time of 1200 s, shared equally for pumping and regeneration) provides significant safety margin against inadvertent overfuelling.

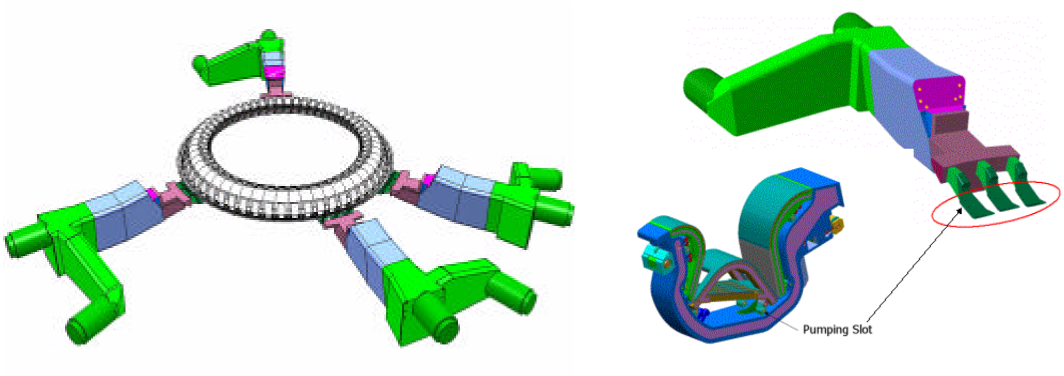


FIG. 1. Left: 3D view of the ITER exhaust gas pumping port geometry showing the connection to the branched and direct cryopumps. Right: Detailed view of the individual divertor cassette and the three fingered connection to the duct, highlighting the pumping slot cross-section.

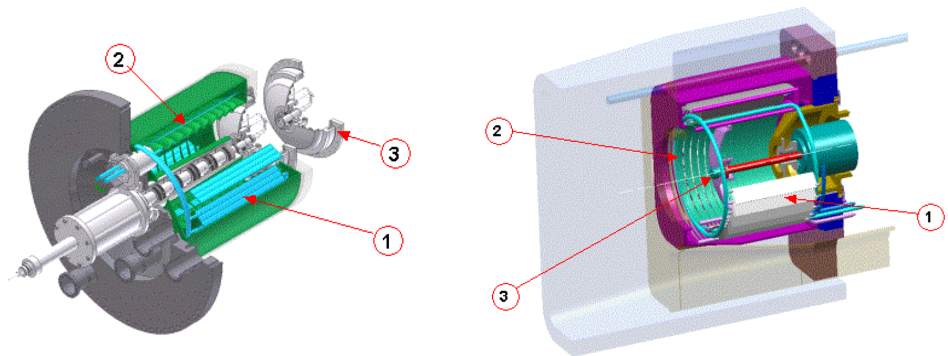


FIG. 2. Comparison of the TIMO model pump (left) and the ITER 1:1 torus exhaust cryopump (right) showing the pumping panels (1), baffles (2) and the inlet valve (3).

In the TIMO test bed at FZK, the model pump (FIG. 2) has been under extensive and fundamental investigation [4] studying pumping, regeneration (thermal desorption pattern) and cryogenic aspects (heat load assessment, LOVA). The model pump cryosorbing panel area, which is from design point of view given by the required helium pump capacity, is composed of a number of identical cryopanels with a design that is similar for all ITER primary cryopumps. Table II lists some of the model pump design details and compares with the corresponding values of the ITER 1:1 pump. TIMO was demonstrated to be a unique and versatile facility to test cryogenic vacuum components and sub-systems for ITER under ITER-relevant conditions in terms of gas flow, temperatures, pressures and cryogenic parameters. In a separate experiment at JET, the panel concept has been fully qualified with respect to tritium compatibility [5].

The discussion in this paper is focussed on the vacuum technological characterisation results. It has been shown that the pumping performance of a high throughput cryopump depends on throughput itself (as operating in transitional flow regime) and gas load. This is why these parameters, related to the pumping surface, were taken as scaling parameters between the model pump and the ITER 1:1 pump. This yields a characteristic surface-related flowrate of $2.5\cdot10^{-4}$ (Pa·m³)/(s·cm²), and a gas load of 0.18 (Pa·m³)/cm².

The efficiency of a cryogenic pump is characterised by the capture coefficient c, which is unity for a black hole under molecular flow conditions; in this theoretical case, all particles approaching the pump inlet cross-section are immediately captured. This integral effect, which is determined by the interior pump geometry, has to be considered separately from the panel-molecule interaction characterised by the sticking coefficient α, which indicates the fraction of particles sticking to the cryosorbent surface related to all particles impinging on it. The sticking coefficient is, among other factors, defined by the sorbent type, its temperature, gas load and history and covers a range of factor 5 at 5 K conditions at the ITER type charcoal between close to unity (for DT) and only about 0.2 (for helium) [6]. The ITER torus cryopump design aims at the capture coefficient depending only very weakly on the kind of gas being pumped. This design target was successfully met for the torus model pump, as illustrated in FIG. 3, which compares experimental results and predictions for the model pump and the ITER 1:1 pump. The results for D_2 which cover a safety-limited gas load only in TIMO, can be extended over the full range, as shown in the complementary JET tests [5]. The maximum capture coefficient under molecular flow operation and at 100% valve opening was calculated to be 0.45 for the model pump, and even higher, about 0.65, for the ITER 1:1 pump (DN 800), respectively. FIG. 3 illustrates the characteristics of both pumps for three different valve openings. It becomes clear that the efficiency is constant at a high level over a broad range of sticking coefficients, which was one of the central objectives in pump design.

TABLE II: DESIGN FEATURES OF THE TIMO MODEL PUMP AND THE ITER 1:1 PUMP.

	TIMO	**ITER**
Inlet valve position	Outside	Inside
Inlet valve diameter [mm]	700	800
Valve stroke [mm]	400	800
Cryopanel system (coated both sides)	4 m² (16 panels, 0.85 m long x 0.15 m wide)	11.2 m² (28 panels, 1 m long x 0.2m wide)
Pump volume [m³]	1 (closed housing)	7 (nude style)

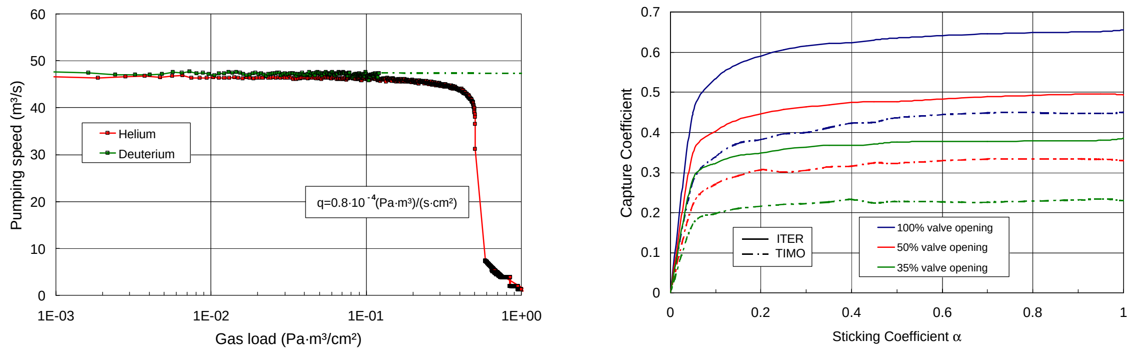


FIG. 3. Left: Experimental pumping speed curves (molecular flow regime) measured in TIMO for D_2 and He. Right: Calculated pumping efficiencies for the model pump and the proposed 1:1 ITER pump.

The measured pumping speeds at the level of the model pump (nominally 50 m³/s for DT in the molecular flow regime) are a good basis for scale-up to the level of the 1:1 pump. Most of the investigated vacuum features and the results of the sorbent characterisation programme do also hold for the full size pump. Based on calculations with the vacuum Monte Carlo code MOVAK3D [7], there results a predicted pumping speed for D_2 of 97.7 m³/s at 100 % valve opening, 73.6 m³/s at 50% and 57.9 m³/s at 35%, respectively for the ITER 1:1 pump. Thus, by increasing the inlet cross-section only by about 30% compared to the model pump and at the same time optimising the inner pump geometry, the achievable pumping speed could be almost doubled. However, the main consequence of the inside valve position is an increase of thermal heat loads into the pump under opened valve conditions. To investigate this, in addition with other aspects, like new cryogen flow distribution patterns and thermal shields, TIMO is currently undergoing an upgrade so as to be able to house the first 1:1 ITER cryopump for closer investigation and do acceptance testing of the serial pumps. As first step towards the upgrade, the model pump will be disassembled and all essential components will be inspected, especially the integrity of the carbon coated cryopanels. So far, no essential component failures have been detected during the four years of pump operation in TIMO.

2.2 Duct Integration: ITERVAC Study

To achieve a sound and balanced design for the complete primary pumping system and to study the influential parameters, simulation calculations were performed for the gas flow through the divertor slots and along the pump ducts into the cryopumps. For the simulation, a dedicated computer code (ITERVAC) was developed [8] which covers all flow regimes from laminar flow (Knudsen numbers of about 0.05) and intermediate flow at the divertor region to molecular flow (Knudsen numbers of about 200) at the cryopump region. ITERVAC represents the flow system as a network of cells with user-defined geometry, determined via input, output, or linking nodes, see FIG. 4. The global data sets for this model were set up for the gases helium, protium, deuterium and tritium.

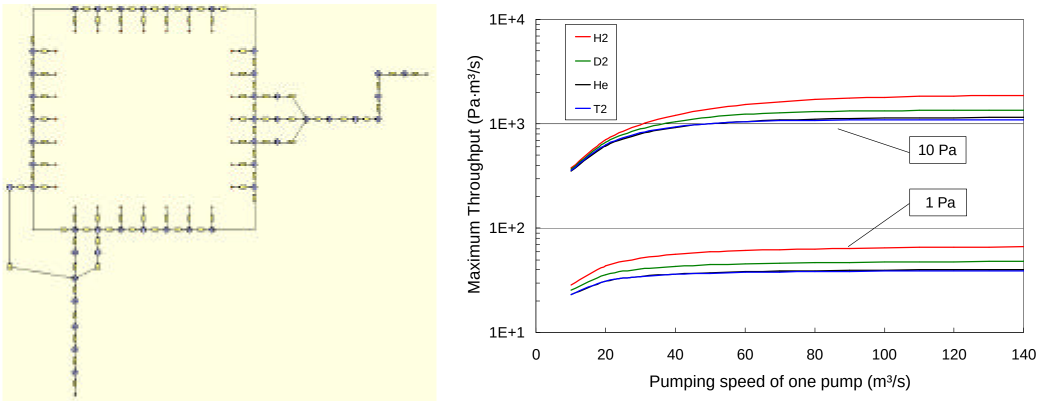


FIG. 4. ITERVAC simulation of the ITER torus exhaust duct and pumping system. Left: Representation of half ITER (two ducts with one in branched and one in direct geometry) as node network, Right: Maximum achievable ITER throughput for 4 different gases at a divertor pressure of 1 and 10 Pa, respectively.

During parametric investigation, it was clearly found that there is a bottleneck of the gas flow coming from the three-fingered entrance section between the divertor cassettes and each pumping duct, see FIG. 1. The maximum throughput at 1 Pa is about 650 (Pa·m³)/s for H_2, but only 38 (Pa·m³)/s for T_2. FIG. 5 reveals that, to achieve the full gas throughput the lowest possible pressure in the subdivertor region is about 2 Pa for the lightest gas H_2, whereas for tritium, this is only achieved at about 2.5 Pa. A sensitivity study was therefore performed in which the divertor finger cross-section (see FIG. 1) was step-wise increased in the ITERVAC model. It was found that it must be increased by 3 cm in both directions to allow for the required throughput at 2 Pa for all gas compositions. Achievement of significantly lower pressures without remarkable changes to the divertor geometry would only be possible by introduction of additional pumping ports.

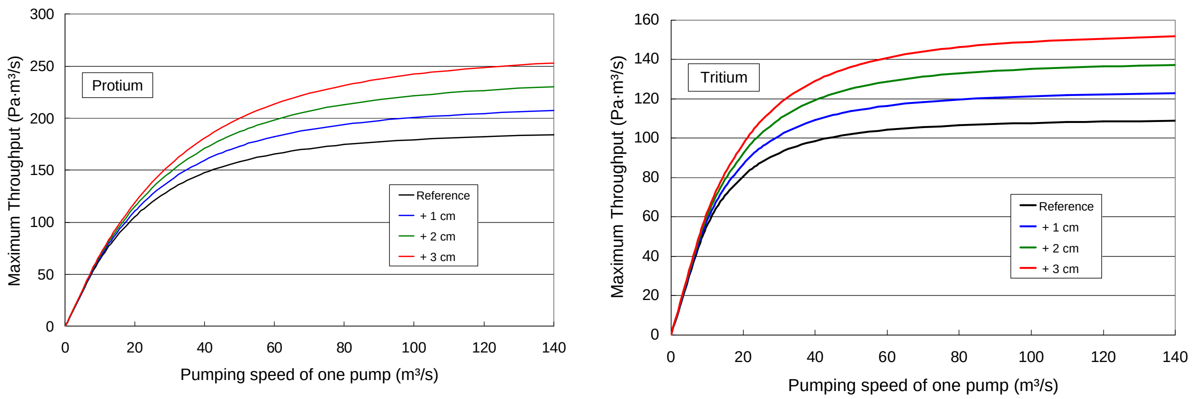


FIG. 5. Maximum achievable ITER throughput for a divertor pressure of 2 Pa for the lightest (H_2, left) and heaviest (T_2, right) hydrogen isotope. The curves highlight the impact of increased cross-sections at each of the three divertor fingers per duct (by 1/2/3 cm in both directions, see FIG. 1).

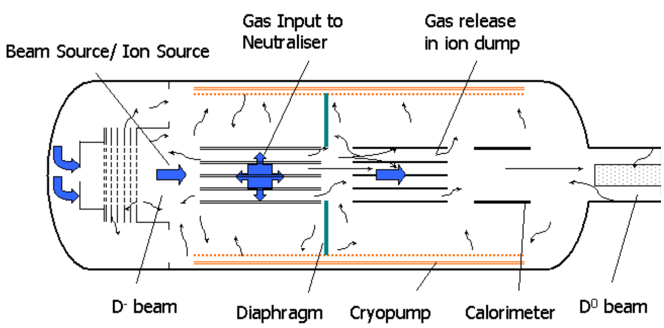
The conclusions to be drawn from the ITERVAC studies are as following:

- The achievable throughput starts to become independent on the attached pumping speed for values above 80 m³/s per pump. The effective pumping speed is dominated by the duct conductance, especially in the divertor finger region.
- This needed pumping speed can be very well provided by a torus pump with a DN 800 mm diameter opening valve and even allows for further valve stroke reduction, which potentially eases the double bellow design (needs further study to functional feasibility).

- The required throughput under plasma burn of 153 Pam³/s can be achieved down to divertor pressures of about 2 Pa in case of lighter hydrogen isotopes. An increase of the divertor finger cassette slot area by about 3 cm would be needed to achieve the requirements at 2 Pa.
- For dwell pumping, the pump is operating in molecular flow regime for most of the pumping cycle; the present effective molecular flow conductance is about 30 m³/s. It looks very difficult to achieve the current dwell terminal pressure target of 0.1 mPa; therefore, assistance by the neutral beam pumping system is currently discussed.

3. The NBI Primary Pumping System

ITER has 2 heating NBI (with provision to add a third one, see TABLE I) and 1 diagnostic NBI system, which is set-up very similar to the others but smaller in size and beam power [1]. The ITER NB system is fuelled by D_2 or H_2. The task of the NBI cryopumps is to maintain low pressure in the injector outside the ion source and the neutralizer, see FIG. 6. The required integral pumping speeds are 3800 m³/s for H_2, and 2600 m³/s for D_2, respectively. The cryopumps are located close to the wall of the beamline vessel. To establish the needed density profile along the beam line of the neutral beam components a diaphragm will be integrated to separate the chambers. Thus, the first chamber with the higher pressure (~ 0.1 Pa) is separated from the second chamber with a ten times lower gas load but a much higher requirement on the vacuum conditions [9].
The pumping panel technology and operation philosophy is the same as that for the torus cryopumps, however the panels are coated only on one side, which is sufficient for the needed hydrogen pumping capacity. Thus, the demand on the cryosupply relative to the pumping surface, and the requirements on the design of the shielding around the pumping low temperature system at 4.5 K are much lower. There will be tritium present since it is foreseen to use beamline pumping to augment the torus dwell pump-down, but the amount will be insignificant compared to the torus cryopumps.
Similarly to the torus cryopumps, the NB cryopumps have to follow a defined regeneration pattern to minimise hydrogenic inventory. The longest reference ITER pulse has a 3000 s burn (with a subsequent dwell time of 9000 s). The NB cryopumps which are not defined for intra-pulse regeneration must have the same total regeneration duration (for each pump) for all plasma burn scenarios. The most demanding reference case is given by the need to regenerate each pump within the dwell period of a 400 s burn standard ITER pulse, namely 1400 s, see [3] for details.



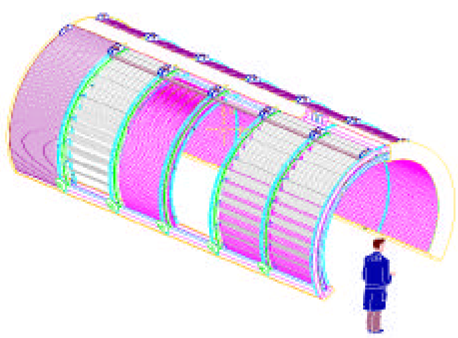


FIG. 6. Schematic set-up of the ITER NBI system, illustrating the various gas sources. The NBI cryopump system, shown to the right, is split in six modules.

4. The Cryostat Primary Pumping System

Before the ITER superconducting magnets and structures are cooled down to liquid helium temperature a stable high vacuum environment (~0.1 mPa) has to be established within the cryostat that envelops the tokamak. In order to standardize cryopump design to the greatest extent, the design of the two cryostat high vacuum cryopumps, located at the lower port level, is practically identical to that of the cryosorption pumps used for the torus primary pumping system, except for the cylindrical casing. On account of the large area of warm vacuum facing surfaces within the cryostat, including epoxy, the pumpdown is dominated by outgassing, in contrast to the other systems operating under very high gas loads.

5. The Forepumping System

A set of powerful mechanical pumps is foreseen to perform the initial pump-down of the torus, cryostat and NBI vessels from ambient pressure as well as the pump-down during regeneration to cross-over pressure (10 Pa) from mechanical to cryogenic pumping. This level is the target ultimate pressure of the forepumps. Each of the three primary vacuum systems is connected to its own roughing pump set via a change-over valve box assembly located in the vacuum pump room, which is at a distance of about 40 m from the torus. A fourth forepumping set is foreseen for service and auxiliary pumping system. The design driver for the size of the mechanical pumps is the limited time during regeneration of NB and torus.
As outlined above, the primary pumping systems are operated in a staggered mode, leaving a regeneration time of 600 s for the torus and 1400 s for the NB system (under minimum repetition time conditions). A cryopump regeneration comprises 4 steps, namely warm-up, gas release, pump-out and cool-down. As study case, an isochronous mode is foreseen, thus leaving one quarter of the regeneration time for pump-down, namely 150 s for the torus system and 350 s for the NB system. In the latter case, this has been recently included to reduce the requirements on the cryogenic system and represents a significant change from former requirements allowing for 960 s. Insufficient pumping speed and/or time will lead to end pressures being higher than 10 Pa, and consequently a higher hydrogen inventory and higher heat loads to the cryosystem. The ITER forepump design is based on two stages of roots pumps (1x4200 m³/h + 2x1200 m³/h) backed by a 4 stage reciprocating piston pump (180 m³/h). As the latter one is not available anymore and in view of the increased requirements, this design has been revised, resulting in a combination of two roots pumps (6000 m³/h and 200 m³/h) backed by a screw pump (630 m³/h) [10]. FIG. 7 illustrates the resulting pump-out of the torus and NBI cryopump volume starting after complete gas release by regeneration. It becomes clear that achievement of the 10 Pa under isochronous conditions necessitates a further upgrade of the forepump train.

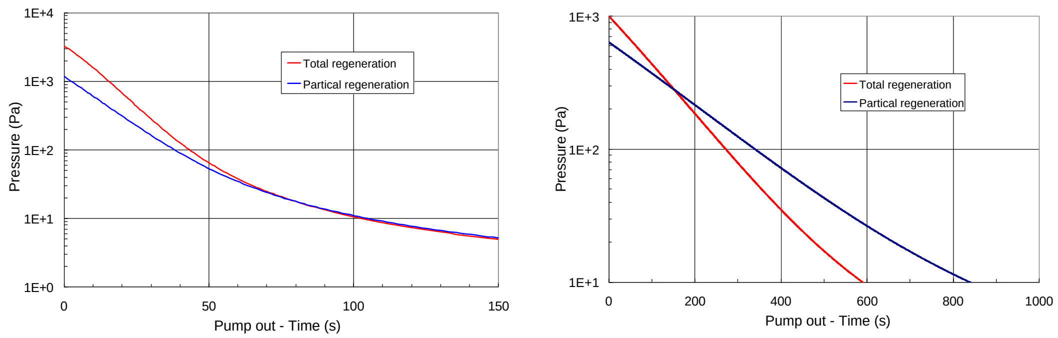


FIG. 7. Comparison of pump-out curves of torus cryopump (left) and NBI cryopump (right). The pump-out curves are calculated for gas temperatures characteristic for regular partial regeneration at 100 K to release the pumped hydrogens and total regeneration at 300 K, respectively.

6. Summary and Outlook

This paper assesses the vacuum technological design of the three big ITER vacuum pumping systems, which incorporate a common cryosorption panel design. The torus exhaust system study has been recently extended to include the complete duct geometry. It could be clearly shown that the divertor essentially limits the effective pumping speed of the torus pumping system. The maximum achievable throughputs and pressures were calculated with a new design code applicable over a very wide range of Knudsen numbers. The code was validated against experimental literature data which, however, were limited to relatively simple geometries. In view of the impact of the calculations, a dedicated test programme for benchmarking the code for ITER relevant complicated duct geometries is under preparation.
The experimental data of the ITER torus model pump as measured in the TIMO facility were evaluated and used as a basis to derive a further optimised design of the ITER 1:1 torus cryopump. The agreement between the Monte Carlo simulation of the model pump and the measured pumping speeds in molecular flow regime was very good.
A similar design approach is under work for the ITER NBI cryopump system within the task of development and design of a 1:1 sized test bed for the ITER neutral beam injector.
The ITER vacuum system design was accomplished by complementary size modelling of the mechanical forepumps, which define the input parameters needed for a proper design of the tritium plant. The interrelation of pump size vs. required pressures and pump-out times is clearly revealed. Extensive efforts are under way to develop high speed tritium compatible roots pumps based on ferrofluidic shaft sealing.

Acknowledgements

This work has been conducted under the European Fusion Development Agreement within the Fusion programme at Forschunsgzentrum Karlsruhe.

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