

Cryopump design for the ITER Heating Neutral Beam Injector

M. Dremel 1), Chr. Day 1), R. Hemsworth 2) R. Pearce 2), C. Mayaux 2)

1) Forschungszentrum Karlsruhe, EURATOM Association, 76021 Karlsruhe, Germany

2) ITER Cadarache JWS, CEA Cadarache, 13108 St. Paul-lez-Durance, France

e-mail contact of main author: matthias.dremel@itp.fzk.de

Abstract. Forschungszentrum Karlsruhe (FZK) is developing the cryopumps for the ITER heating neutral beam injectors. The system is characterized by high gas flows coming from different sources against which the cryopumps must maintain a pressure between 10^{-2} and 10^{-3} Pa in the beam line vessel. In the close arrangement of the beam line the size of the cryopump is limited to a flat rectangular geometry of 8 m length, 2.75 m height and a depth of 0.5 m. Two cryopumps of this size will be included in each beam line. Within gas profile calculations of the detailed beam line geometry it showed up that the gas capture probability of the pumping surface must achieve 30 % to guaranty the beam pulse operation.

This paper describes the vacuum requirements given by the ITER heating neutral beam injector and presents gas profile calculations of different beam line configurations to outline the effect on the operation of the cryopump. The design of the novel cryopump is presented and the heat load calculations to the cryogenic circuits will be discussed and summarized for the different operation scenarios. It is shown that the cryopump for the ITER heating neutral beam injectors covers all vacuum requirements and it is adapted to the ITER cryogenic supply.

1 Introduction

The ITER heating neutral beam injectors will be operated with protium H_2 and deuterium D_2 . The objective of the cryopump is to pump the large gas flows from different sources and maintain low pressures during the entire duration of the beam pulse operation. The application needs vacuum pumps with high pumping speeds for hydrogen in the range of several 1000 m^3/s . This can be done by titanium sublimation pumps often used in test facilities for neutral beam components but they are limited to short pulse operations of several seconds. For the ITER operation pulse duration times of one hour are foreseen and therefore the vacuum requirements can only be met by cryogenic pumps accumulating the gas on cold surfaces.

Condensation and adsorption are the two different concepts which can be used to realize the pumping of the gases.

In the former case, to condense the protium gas fluxes occurring during the beam pulse operation of the ITER heating neutral beam a surface temperature of ≤ 4.2 K is needed. For the very large cryopumping systems of the injectors this would be a high demand because the inlet temperature of the forced flow cooling would have to be about 3.5 K and no bath cooling at this temperature is provided. In addition, for condensation pumping the temperature gradient for the cooling must be small and therefore large cryogenic mass flows are needed to ensure a stable pumping without oscillations of the pumping speed. The high mass flows lead to a high pressure drops across the cryogenic circuits and result in an additional heat load by the helium circulation blowers.

Such a cryogenic supply would be highly demanding and is not provided within the ITER cryoplant. To cool the cryopanel it is foreseen to use a forced flow of supercritical helium at 4 bar (a) and an inlet temperature of 4.35 K. Therefore pumping by adsorption on activated charcoal is used with several advantages. The adsorption of deuterium gas is guaranteed up to charcoal temperatures of about 15 K and also protium will be pumped sufficiently to fulfil the vacuum demands of the ITER neutral beam injectors for much higher surface temperatures than needed for condensation pumping. Thus, the requirements to the cryogenic supply are strongly relaxed. The allowed outlet temperature will be about 6.7 K and the mass flow for cooling the cryosorption panels is strongly reduced and as a consequence the pressure drops.

2 Vacuum requirements of the ITER heating neutral beam injectors

The reference design of the ITER Neutral Beam Injector is shown in figure 1 including the main gas sources. The complex geometry of the ion source and the resulting pressure profile in the accelerator is discussed in detail in reference [1]. For the discussions in this paper the gas flow from the ion source is simplified to a gas flux from the beam source vessel into the beam line vessel.

In the beam line vessel the cryopumps are pumping all gas fluxes from the beam source vessel the neutralizer and the Residual Ion Dump (RID). The ion beam is neutralized with an efficiency of 60% in a gas cloud in the neutralizer. To reduce the needed gas flux to tolerable flow rates the neutralizer is split into 4 channels to get a smaller gas conductance und thus reducing the needed gas throughput for the neutralization of the ion beam. The RID behind the neutralizer deflects the not neutralized part of the beam leading to a small additional gas flow from it. Finally a calorimeter is installed which can be opened for beam energy deposition in the tokamak plasma or closed in case of test operation of the beam line.

The main gas load (about 80% of the total) comes from the neutralizer. Against this gas flow and the additional flow from the ion source a pressure between the accelerator and the neutralizer below 0.02 Pa must be maintained. Downstream of the neutralizer towards the RID several 10^{-2} Pa can be allowed but after the RID the pressure should be minimized as much as possible to reduce the re-ionization of the neutralized beam. A pressure in the range of 10^{-3} Pa is used as a required target value making even the small gas flow out of and through the RID a demanding situation for the cryopump.

To optimize the pressure profile along the beam line gas baffles can be integrated which split the entire beam line vessel into separated chambers. Thus in some critical areas of the beam line the pressure can be reduced while in other less critical regions the pressure is increased. In figure 1 this gas baffle is included at the start of the RID and the beam line geometry and the position of the gas sources next to the cryopump position and size are shown. The occurring gas fluxes for deuterium and protium operation are summarized in table 1.

2.1 The cryopump design of the ITER neutral beam injectors

The cryopumps are based on sorption pumping by low temperature charcoal coated cryopanel operated between 4.35 K and 6.5 K. In order to minimize the heat loads to the cold pumping surfaces they are well protected by radiation shields, usually a chevron baffle. The gas capture probability of such a classical cryopump is limited to 24% mainly by the gas conductance through the chevron baffle.

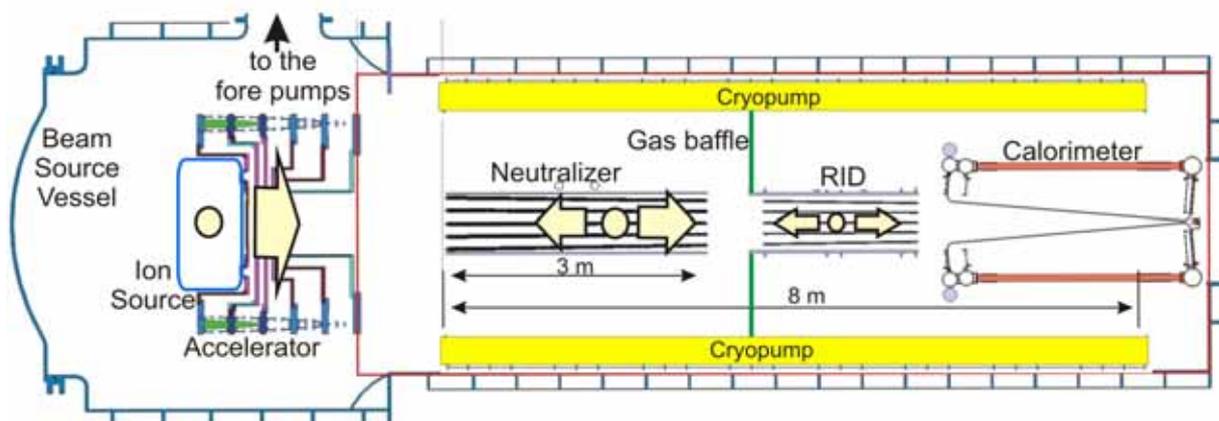


FIG. 1. Drawing of a sectional cut of the ITER heating neutral beam injector, including the gas sources (circles) and the gas flow directions (arrows).

TABLE 1, GAS THROUGHPUTS OF THE ITER HEATING NEUTRAL BEAM INJECTOR FOR PROTIUM AND DEUTERIUM OPERATION (*FOR THE CONFIGURATION WITH THE HIGHEST GAS FLOWS)

	H ₂ operation [Pa·m ³ /s]	D ₂ operation [Pa·m ³ /s]
Ion Source*	6.9	4.9
Neutralizer	27	19
RID	0.38	0.38
Overall	34.3	24.3

The resulting pumping speed of this cryopump design would not cover the needed pressure profile of the heating neutral beam injectors. To fulfil the requirements a novel cryopump design has been developed which is characterized by an increase in capture probability of 50% which could be achieved at a corresponding increase of the heat load of only 20% compared to a classical cryopump with a chevron baffle. For reasons of thermal hydraulics and manufacturing issues the 8 m long cryopump has been split into 8 modules, each of them 2.75 m high and 1 m wide. Each of these modules consists of 4 pumping sections as depicted in figure 2. One entire cryopump will consist of 8 modules with 32 sections, one next to each other, without separating intermediate walls between the sections.

Each of the 3 stages (*see FIG. 2*) of one section has its own hydroformed radiation shield resulting in an open structured cryopump with a high capture probability for gas particles. For the use in a neutral beam facility the gases to be pumped are protium and deuterium with a sticking coefficient to the charcoal of 0.7 for H₂ and 0.95-1 for D₂ [2]. By the use of 3D Monte Carlo models the detailed cryopump design has been elaborated and the overall capture probabilities of the cryopump have been determined. In the case of deuterium a gas capture probability of 33% and in case of protium 30% has been achieved.

2.2 Calculation of gas profiles

For the determination of the needed pumping speed and the preferable position of the gas baffle, detailed 3D models of different beam line geometries have been prepared to calculate the gas density distribution along the entire beam line using the ITER reference code for gas distribution calculations "MC-GF code". The results of complementary calculations are discussed in [3, 4]

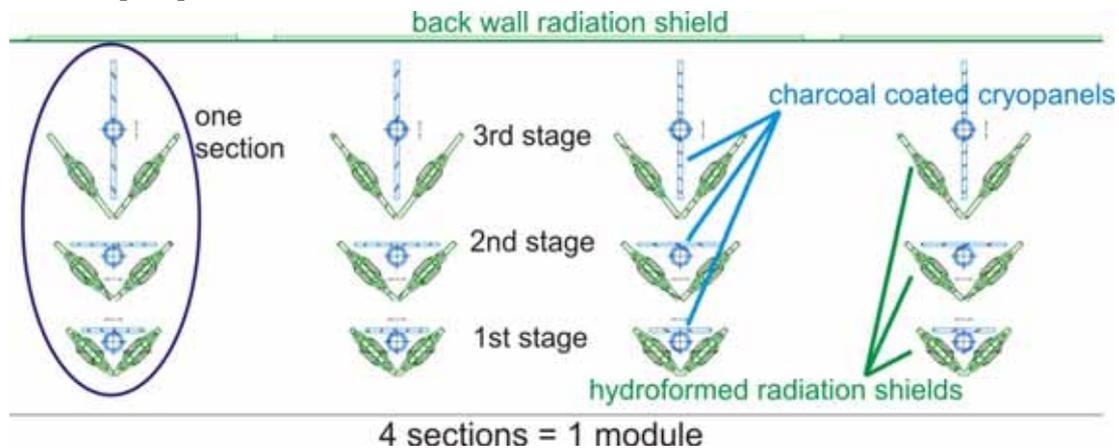


FIG. 2. Sectional cut of one module of the cryopump for the ITER heating neutral beam injector. Radiation shielding in green colour, cryosorption panels in blue colour.

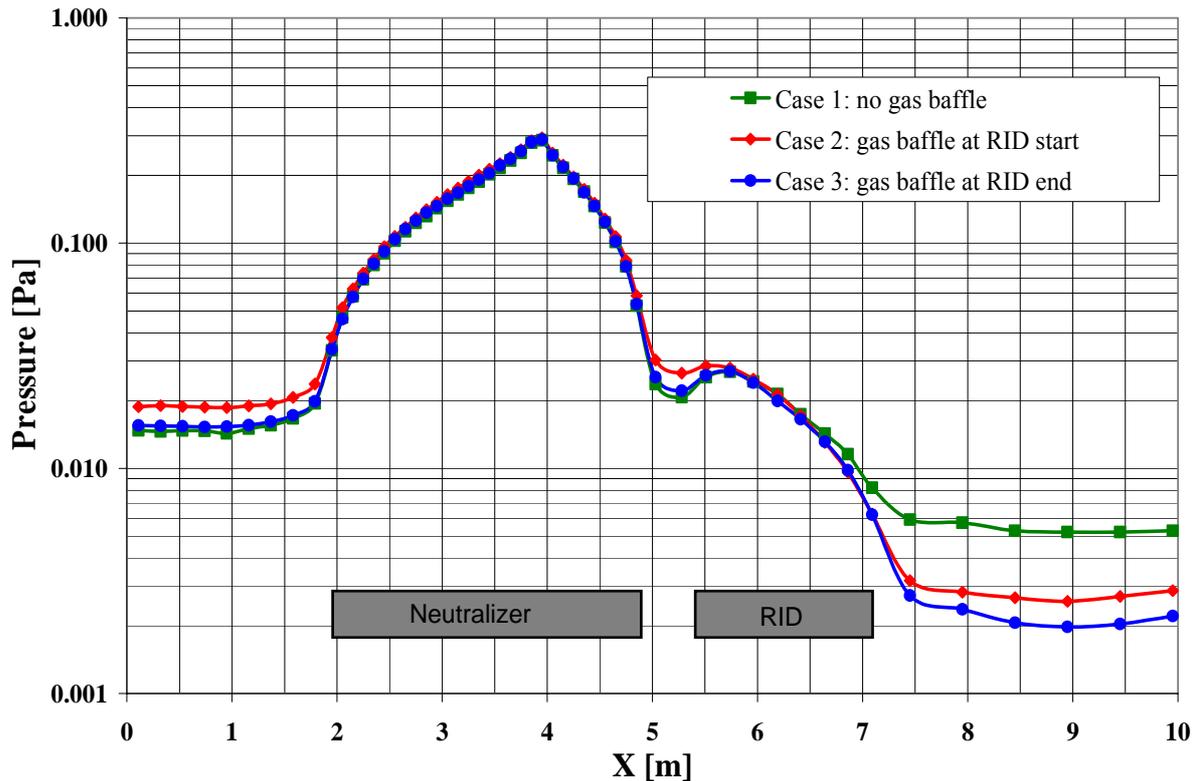


FIG. 3. Calculated gas profiles for 3 different positions of the gas baffle.

One important purpose is to reduce the pressure between the accelerator and the neutralizer below 0.02 Pa which can be done by several approaches:

The cryopump should be located as close as possible at the critical area to be pumped but it can not be moved upstream across the edge of the neutralizer entrance due to the strong local heat loads from high energy electrons. Those electrons come from co-accelerated electrons backscattered from the electron dumps near the neutralizer entrance. Therefore the gas profiles are calculated with the start of the cryopump at the neutralizer start position and not moved further upstream to the critical area even though that gives a better effective pumping speed in that region.

The pumping speed can be increased by increasing the gas capture probability of the cryopump design or the size of the pump. Therefore, the pump has been designed with a maximized height of the pumping area, reducing the space for the manifolds as much as possible and under consideration of the actual beam line design.

The gas capture probability of the cryopump depends on the detailed design of the pump. Even with the maximized size the classical cryopump would not cover the needed pressures during beam pulse operation. An open structured cryopump has higher heat loads to the pumping surfaces but can also achieve a higher capture probability. Usually the pumps must be carefully adapted to the system in which they are integrated.

A further possibility to reduce the pressure in front of the neutralizer is to move the gas inlet position in the neutralizer downstream towards the RID. To get the same gas target for the neutralization of the ion beam the gas throughput must be increased by 12 % compared to the gas inlet position in the middle of the neutralizer. Nevertheless, this change reduces effectively the pressure between the accelerator and the neutralizer.

The used geometry for the beam line components is taken from the ITER reference design. The beam line vessel has a length of 10 m, the cryopumps a length of 8 m with a height of the pumping area of 2.3 m. The neutralizer is 3 m long and the gas inlet position is at 2/3 of its

lengths downstream the beam line. A distance of 0.5 m to the 1.8 m long RID has been used and both components are split into four rectangular channels with a height of 1.7 m and a width of 0.1 m. The calorimeter has a distance to the RID of 0.2 m and a length of 2.8 m. For the presented investigations only the closed calorimeter configuration has been considered. The calculations have been carried out using isothermal conditions at 300 K for the gases and all surfaces.

The position of the gas baffle has a strong impact on the gas pressures in the beam line vessel. In the ITER reference design a gas baffle at the start of the RID is foreseen to reduce the pressure towards the duct and minimize the reionisation losses of the neutralized beam. In figure 3 several gas profiles along the beam line are depicted for different assemblies of the gas baffle. In case 1 no gas baffle is included. In case 2 one gas baffle is located at the start of the RID and in case 3 one baffle is integrated at the end of the RID. No gas baffle as in case 1 leads to a higher pressure towards the duct and thus to an increased reionisation of the neutralized beam. The use of one baffle at the entrance of the RID would result in a 25% higher pressure in front of the neutralizer than for the cases one and three. To install the baffle at the end of the RID would result in a pressure of 0.015 Pa in front of the neutralizer and into the smallest pressure behind the RID. As regards the pressure profile and the operation time, which will be discussed in section 2.3, case 3 would be the preferred solution.

2.3 Assessed beam pulse operation times

The beam pulse operation times have different limitations depending on whether protium or deuterium is used. In the case of protium pumping the pumping speed decreases with the amount of already accumulated gas to the charcoal. This well known effect leads to a reduction of the pumping speed by about 10 % after an adsorption of $1000 \text{ Pa}\cdot\text{m}^3$ protium to one meter square of charcoal coated surface. Assuming a linear decrease for higher gas loads the critical pressure between the accelerator and the neutralizer is reached after an accumulation of about $2000 \text{ Pa}\cdot\text{m}^3$ of protium. The given charcoal area and the related gas flow to it depend on the position of the gas baffles, because they split the entire cryopump and separate the flows from the components. The most stringent situation occurs for case 2 when one baffle is used at the start of the RID. In this case the pressure limit of 0.02 Pa is reached after 1400 s. In case 3 with the baffle at the end of the RID an operation time of about 2000 s with protium is possible and without any baffle the operation time would increase to 3000 s. The saturation effect due to the accumulation of deuterium is much less pronounced than due to the accumulation of protium. Therefore the operation time for deuterium pulses is given by the administrative deflagration limit which is set for hydrogen at a gas concentration of 1.5 mol/m^3 . This concentration limit must be followed during the regeneration of the cryopumps after deuterium operation. With the volume of the vessel of 200 m^3 and a gas temperature of 300 K the operation time with deuterium is limited to 7.5 h. If the capacity limit of the charcoal for deuterium is reached before must be experimentally detected.

3 Heat loads to the cryogenic circuits

The heat loads to the cryogenic circuits must be calculated for different operation scenarios which are steady state operation, beam pulse operation and finally the 100 K regeneration with a heat transfer determined by gaseous heat conduction through the released gas.

In steady state operation the thermal radiation from the beam line components dominates the integral heat load. The beam line components are water cooled and a temperature of 100°C as the outer surface temperature has been used for the calculations. The temperature of the vessel is assumed to be 300 K and no gasloads are expected in steady state conditions.

The heat loads by thermal radiation have been calculated using the exact viewing factors ϕ_{12} which characterize the geometrical alignment of the hot surface (1) to the cold surface (2) [5]. These coefficients have been determined using detailed three dimensional models of the cryopumps within a Monte Carlo code (MOVAK3D). The heat transfer between two surfaces by thermal radiation Q_{12} is finally calculated for all the surfaces between a pumping section and its vacant pumping sections by:

$$Q_{12} := \frac{e_1 \cdot e_2 \cdot A_1 \cdot \sigma_B \cdot \phi_{12}}{1 - (1 - e_1) \cdot (1 - e_2) \cdot \phi_{12} \cdot \phi_{21} \cdot \frac{A_1}{A_2}} \cdot (T_1^4 - T_2^4)$$

e: Emissivity, A: Radiating areas, ϕ_{12} : Viewing factor from surface 1 to surface 2,
T: Temperatures, σ_B : Stefan Boltzmann constant

This extensive method was used because of the complex surface arrangement of the new cryopump design. Compared to the former designs the heat load by 300 K radiation from the beam line plays an important role. Therefore the coating of the surfaces is very important to derive finally with the minimized heat load on the 5.5 K circuits. The final results of these investigations are depicted in figure 4.

3.1 Heat loads to the charcoal coated cryopanel in steady state operation

The surfaces of the 5.5 K circuits are coated with activated charcoal and split into 3 stages as the shielding. Stage 1 and 2 are only on the side facing to the back walls coated with charcoal. Stage 3 which is turned by 90° is coated on both sides to increase the pumping surface and thus the possible operation time for protium pulses.

In case of the low temperature circuit the overall sum of the heat load by thermal radiation is split into a load by direct radiation from the thermal shielding and the load by the radiation from the beam line reflected via the shielding onto the cryopanel. Due to the Stefan-Boltzmann law (radiated power $\sim T^4$) the 300 K radiation is dominant compared to the radiation from the shielding at 85 K. Therefore, the many parts of the radiation shield must be blackened except of the first stage and the back sides of the radiation shielding facing to charcoal coated cryopanel. In addition all non charcoal coated surfaces of the low temperature circuit must be electropolished to minimize the heat load. The blackening of the radiation shielding is made by a plasma spray coating with $\text{TiO}_2/\text{Al}_2\text{O}_3$ which provides an emissivity of $e = 0.95$. The emissivity for the charcoal coated surfaces and for the electropolished surfaces are assumed to be $e = 0.9$ and $e = 0.15$.

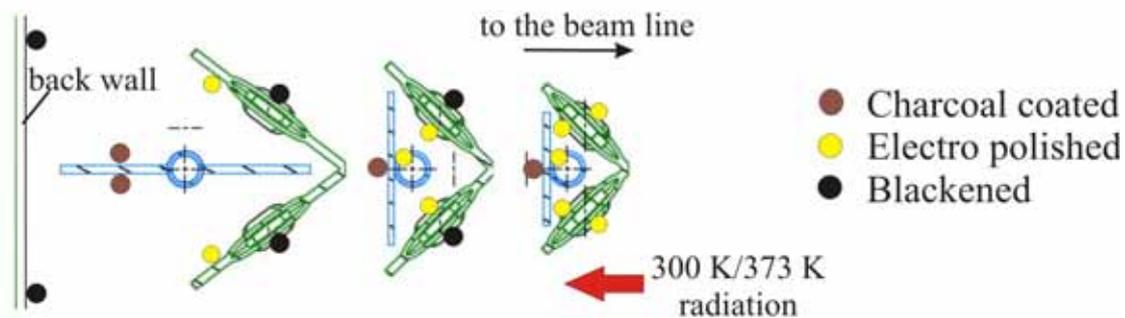


FIG. 4. One of the 64 pumping sections with the optimized coating of the surfaces to achieve the smallest heat load to the low temperature circuit (in blue colour).

TABLE 2, HEAT LOADS TO THE CRYOPANELS AND THE RADIATION SHIELDING.

	Charcoal coated cryopanel	Radiation shielding
Thermal radiation:	152 W	11.6 kW
Solid heat conduction:	78 W	0.32 kW
Steady state:	230 W	11.92 kW
Cooling of gas	90 W	0.035 kW
Gaseous heat conduction	14 W	0.03 kW
Adsorption enthalpy	21 W	-
Scattered electrons	160 W	19 kW
Steady state	230 W	11.92 kW
Beam pulse operation:	515 W	31 kW
100 K Regeneration	-	24 kW

Within an iterative improvement of the inner cryopump geometry the gas capture coefficient of the pump has been maximized with first priority and as second priority the heat load to the low temperature circuit has been minimized as far as possible. The solid heat conduction between the supports of the cryopump at 300 K to the radiation shielding and between the radiation shielding to the cryopanel circuit is the second significant part which must be added. The calculated values are given in TABLE 2.

3.2 Heat loads to the charcoal coated cryopanel in pulse operation

During beam pulse operation one significant heat load is given by the gas loads. The heat load to the cryopanel is increased by the cooling of the gas from the temperature of the impinging gas molecules to 5.5 K, by the adsorption enthalpy of the accumulated gas to the activated charcoal and by gaseous heat conduction between the shielding and the cryosorption panels. The heat load by scattered electrons from the neutralizer edges is assessed to be of the same order and thus an important load, because it is localized on the first module of the cryopump (see TABLE 2).

3.3 Heat loads to the radiation shielding

In steady state operation the thermal radiation from the beam line components and the beam line vessel results to a heat load of 11.6 kW to the radiation shielding. This value has been determined by the calculation of the exact viewing factors between the beam line components and the cryopump. For the temperature of the beam line vessel and the beam line components 300 K and 373 K have been used, respectively, and the emissivity of both surfaces was set to $e = 0.3$.

The additional heat load by solid heat conduction from the supports at 300 K is conservatively assessed to about 320 W. The load by the gas fluxes during the beam pulse operation is below 100 W. This is resulting in a heat load of 12 kW distributed more or less homogeneously across the cryopump. But the main additional heat load during beam pulse operation is due to high energy electrons due to backscattering from electron dumps. This is an additional and dominating heat load which is estimated to be ≈ 19 kW localized on the first part of the cryopump and leading to an integral heat load of 31 kW during beam pulse operation.

4 Engineering design and thermal hydraulics

The engineering design of the cryopump is mainly steered by the pipe routing of the cryogenic circuits. The important issues are to reduce the pressure drops across the circuits as much as possible but still maintaining good flow distribution uniformity and also to guarantee a stable cooling of the entire cryopump during all operation scenarios. For a reliable cooling the local heat loads especially at the start of the cryopump must be taken into account. Therefore a series connection of the pipework of the 8 modules of each cryopump was chosen as the most reliable solution. To minimize the pressure drop across the low temperature circuit only pipes have been included in the entire circuit. Hydroformed components with complex inlet/outlet geometries and high resulting pressure drops are only used for the radiation shields.

The cryogenic circuits are designed for the supply by the ITER cryogenic plant which foresees an operation pressure of 18 bar for the cooling loop of the shielding. Both cryogenic circuits must be able to be operated under these conditions and all components including the hydroformed front shields and back walls are designed for it. Next to this the pressurized circuits of the cryopump are complete stainless steel structures to reduce mechanical stresses during cool-downs and warm-ups and minimize the risk of leaks.

Based on the thermal hydraulic investigations the design of the pipe routing has been developed accompanied by the development of a support structure of the cryopumps. This work included stress and strain analyses of the cryopumps to detect the highest allowable temperature gradient across the cryopump during the warm-up and cool-down operation [6].

Summary

The new cryopump design is the reference design for the ITER Heating Neutral Beam Injectors and the mechanical engineering has been finished to come up with the design in terms of a detailed CATIA5 model. Two cryopumps will be integrated for one injector, each of them 8 m long and 2.75 m high resulting in an overall pumping speed for protium of 5000 m³/s.

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