THE NEUTRAL BEAM TEST FACILITY CRYOPUMPING OPERATION : PRELIMINARY ANALYSIS AND DESIGN OF THE CRYOGENIC SYSTEM .

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ABSTRACT

The ITER neutral beam heating and current drive system is to be equipped with a cryosorption cryopump made up of 12 panels connected in parallel, refrigerated by 4.5 K 0.4 MPa supercritical helium. The pump is submitted to a non homogeneous flux of H_2 or D_2 molecules, and the absorbed flux varies from 3 $Pa.m^{-3}.s^{-1}$ to 35 $Pa.m^{-3}.s^{-1}$. In the frame of the “ITER first injector and test facility CSU-EFDA task” (TW3-THHN-IITF1), the ITER reference cryosystem and cryoplant designs have been assessed and compared to optimised designs devoted to the Neutral Beam Test Facility (NBTF). The 4.5 K cryopanel, which has a mass of about 1000 kg, must be periodically regenerated up to 90 K and occasionally to 470 K. The cool-down time after regeneration depends strongly on the refrigeration capacity. Fast regeneration and cool-down of the cryopanels are not considered a priority for the test facility operation, and an analysis of the consequences of a limited cold power refrigerator on the cooling down time has been carried out and will be discussed. This paper presents a preliminary evaluation of the NBTF cryoplant and the associated process flow diagram.

INTRODUCTION

In the frame of the “ITER first injector and test facility CSU-EFDA task” (TW3-THHN-IITF1), the ITER reference cryosystem and cryoplant designs have been assessed and then compared to optimised designs devoted to the neutral beam test facility (NBTF). The NBTF includes a large cryopump which must operate under ITER representative operating conditions.

The cryogenic system will have to be able to refrigerate the NB Test Facility Cryopump in “acceptable” and “representative” operating conditions during short (20 s) and long pulses (3600 s). It is important to consider the system reliability, cost optimisation and the procurement and installation schedule.

CRYOPUMP DESIGN OVERVIEW

The cryopump [1] designed by FZK is made up of three parts which are: the 4.5 K cryopanels, the 80 K shields and the 80 K chevrons baffles. The cryopanels located in between the external shields and the chevrons baffles each consist of fourteen panels connected in series, which are coated on one face with activated charcoal.

OPERATING REQUIREMENTS

During standby and pumping operating mode, the cryopanels are maintained at a temperature of 4.5 K, by supercritical helium circulation, whilst the shields and chevrons baffles are cooled to ≈80 K by gaseous He. The activated charcoal on the cryopanels must be warmed up to 90 K to release all the H_2, or D_2, trapped during beam operation. In this phase, the shields and the chevrons baffles have to be maintained at a temperature close to 90 K. Regeneration at 470 K is foreseen for the ITER injector cryopumps in order to remove other (impurity) gases from the charcoal. This is not essential on the NBTF but its feasibility could be demonstrated. In this operation, only the cryopanels have to be heated up to 470 K. The shields and baffles could be maintained at a temperature close to 300 K if the cryopump design can accept the consequent differential thermal expansion. If this is not the case, the cryopanels, the shields and the chevrons baffles can be fed in series in order to limit the temperature differences between the three parts. The disadvantage of such a process is that a greater mass has to be heated which increases the time needed to cool the pump back down to the operating temperatures.

CRYOGENIC LOSSES

In long pulse pumping mode: The refrigeration power required by the cryopanels at 4.5 K results from the various heat loads such as: radiation from shields and baffles; radiation transmitted through the baffles; conduction from shields and baffles through the supports and the residual gas; and thermalisation of the incoming gas. The refrigeration power needed to maintain the external shields and the chevron baffles at 80 K results also from the various heat loads such as: radiation from the external wall; radiation from the beamline components; pre-cooling of the pumped gas rom 350 K to 80 K, conduction through the residual gas from the external wall to the shields, and conduction through the supports. The total heat loads are: 150 W on the 4.5 K cryopanels, and 18.5 kW on the 80 K shields and chevrons baffles (FZK and CEA estimations).

During regeneration at 90 K, the released H_2 or D_2 will result in a fast rise in pressure and consequently an increase of the heat load by conduction through the gas from the 300 K external wall to the 80 K shields and from the internal beamline components to the chevrons baffles. The load due to conduction through the residual gas, which is proportional to the distance between warm and cold surfaces, can reach 30 kW in the ITER reference design where there is only 60 mm between vessel wall and the external 80 K shields. The heat transfer by conduction between shields, baffles and cryopanels will tend to reduce the temperatures differences between the various parts of the cryopump.

ASSESSMENT OF CRYOGENIC ITER COMPONENTS

The total cold power needed for ITER at 4.5 K is 43.2 kW + 0.17 kg.s^{-1} of LHe, which is to be supplied by 4 identical LHe process modules each of 18 kW at 4.5 K, whereas the cold power required at 80 K, 987 kW, is supplied by two 80 K helium loops and an LN2 subsystem each of 500 kW. Taking into account the very big difference between the needs of ITER and of the NBTF (150 W at 4.5 K), the ITER reference solution appears not to be well adapted to the NBTF, (see Figure 1).

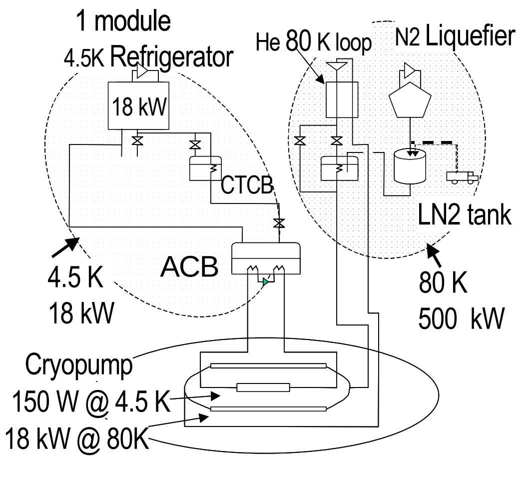

Fig 1: The NBI test facility cryosystem based on the ITER cryoplant components

ALTERNATIVE CRYOSYSTEM PROPOSED FOR THE NBTF

Two alternative solutions are proposed for the NBTF cryoplant, that are optimised in terms of reliability, 4.5 K cooling power, 80 K cooling power, cost and development. A standard, industrial, 4.5 K refrigerator cryosystem is proposed, (see Figure 2). This has an available maximum cold power of 500 W at 4.5 K in pure refrigerator mode and 150 l/h of LHe in pure liquefier mode. The cold power at 80 K has to be produced by an extra 80 K refrigeration module, for which two possible alternative options are proposed, (see Figure 3). The first system uses a cold circulator to generate a helium flow which is thermalised by liquid nitrogen at atmospheric pressure. The second system operates with a helium Bryton cycle that includes mainly a compressor, a counter flow heat exchanger and an expander. In order to compare the two systems, one can say that the Bryton system has a lower operating cost and allows a progressive cooling down of the shields and baffles, and that using an 80 K cold circulator and LN2 bath results in a very high LN2 consumption (≈10000 l per day) during operation. However, for optimised efficiency a Bryton cycle system must be operated with a high delta T to minimise the required helium flow rate and consequently the electric power consumption of the compressor. The CEA prefers to promote the Bryton cycle solution. The process diagram is represented on (Figure 4).

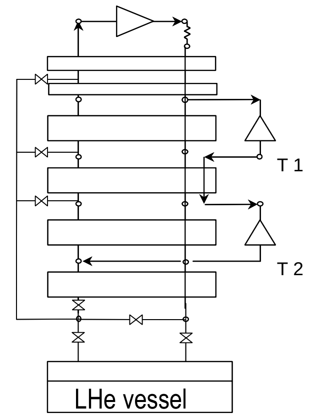

Fig 2: Standard 500W, 4.5K refrigerator

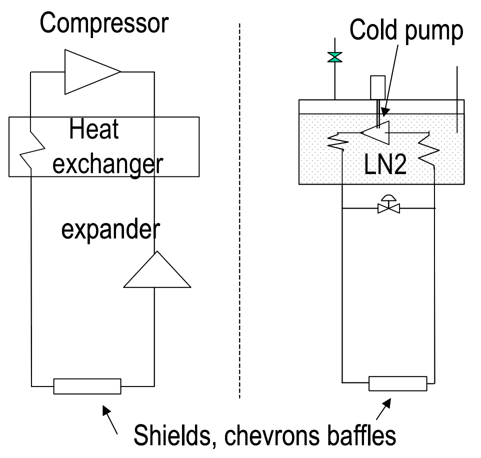

Fig 3: 80K Refrigeration loop

OPERATING CONSTRAINTS

In long pulse operating mode: The cryopanels are fed by the 4.5 K Joule-Thomson supercritical helium flow with a mass flow rate of 0.03 $kg.s^{-1}$ inducing 1.5 K of delta T with a pressure in the cryopanels higher than 0.4 MPa. Liquid helium contained in a storage tank imposes a constant temperature at the inlet of the cryopanels and allows an added cold power by evaporating liquid helium if necessary. This Joule-Thomson flow is then expanded throw the J-T valve producing liquid helium that is stored in the liquid helium tank.

Through the second 80 K refrigerator option, the shields and chevrons baffles are refrigerated from the Bryton cycle by gaseous helium with an inlet temperature of 66 K and an outlet temperature of 90 K corresponding to 0.150 $kg.s^{-1}$ of He flow. The cold power supplied by the expander is about 22 kW and the electric consumption is ≈250 kW. In 90 K regeneration mode: the Bryton cycle supplies the cryopanels, shields and baffles which are connected in series, the outlet of the shields being coupled with the inlet of the cryopanels in order to fix the temperature at 90 K at the inlet of the cryopanels. An outgassing process will start progressively with the rise in temperature of the first cryopanels. The released gas will be mainly pumped by the other cold cryopanels and partly by the forepumping system. The outgassing will be completed when the last cryopanel is warmed-up to 90 K. If the quantity pumped by the cryopanels is far from

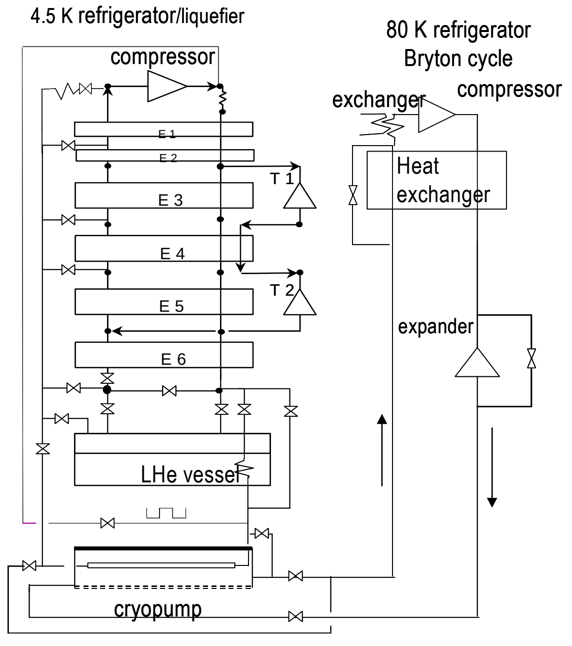

Fig 4 : Process flow diagram

the saturation capacity, a maximum of outgassing is foreseen when the last cryopanel is heated. During this phase the additional heat load by conduction through the residual gas from the vessel wall to the external shields and from internal beamline components to the baffles will rise becoming higher than the cold power provided by the expander, resulting in a temperature increase of all parts of the cryopump .This increase in temperature depends on the forepumping efficiency via the pressure in the NBTF vessel and the time duration.

In 470 K regeneration mode: The cryopanels must be warmed up to 470 K by hot He gas circulation. The He gas is taken at 300 K from the outlet of the compressor and then heated by an electric heater. This gas has to be cooled back down to room temperature before returning to the compressor. A significant power (15 kW) is radiated from the cryopanels at 470 K to the shields and baffles which must be extracted by a heat exchanger, see Fig 5, before flowing back to the Bryton compressor. Due to the low mass flow at the compressor (0.080 $kg.s^{-1}$) that is available to warm-up the cryopanels, a high delta T appears between the inlet and outlet of the cryopanels. The consequence is that a high inlet temperature of the gaseous helium is required in order to be able to reach the specified 470 K temperature at the outlet of the cryopanel. The required power is about 40 kW.Cooling down the cryopump: The cooling down of the cryopanels is carried out with the 1 kW cold power supplied by the two turbines of the refrigerator. The time duration to cool the 1000 kg cryopanels from 300 K to 4.5 K is about 26 h. The cooling down of the shields and baffles is progressively achieved by the Bryton cycle with the cold power supplied by the expander. The time duration to cool down the 5700 kg of shields and baffles from 300 K to 80 K is about 10 h.

Cooling down after the 90 K regeneration: The cryopanels have to be cooled down using the flow from the refrigerator, thermalised at 4.5 K in the liquid helium bath. The available mass flow rate of 0.030 $kg.s^{-1}$ leads to a cool down time from 90 K to 4.5 K of 550 s. During this phase a part of the cold power is delivered by the evaporation of LHe contained in the 1000 l liquid helium storage tank.

Cooling down after the 470 K regeneration: The cool down of the cryopanels from 470 K to 4.5 K is divided in two phases, first the cooling down from 470 K to 300 K room temperature, then the cooling down from room temperature to 4.5 K. During the first phase the helium flow available of 0.080 $kg.s^{-1}$ is directly taken from the outlet of the compressor at room temperature. The time duration of this phase is about 1 h. The second phase is identical to the cooling down describe above.

CONCLUSION

The presented solution which include a standard 4.5 K refrigerator/liquefier and an 80 K helium Bryton cycle appears well adapted to supply the neutral beam test facility cryopump. Nevertheless some points still remain to be clarified, specially during transient of operation. The 90 K regeneration constitute one of the phases that are rather difficult to predict:

-firstly from the point of view of the pressure evolution during outgassing of hydrogen or deuterium due to a progressive warm-up of the cryopanels that are connected in series.

-secondly from the point of view of the additional heat loads due to the molecular conduction from the warm vessel wall to the shields and from the internal beamline components to the chevron baffles. This present work has to be considered as the first stage in defining a cryosystem which could satisfy the expressed operating specifications of the NBTF cryopump. It will have to be subjected to more detailed studies by the suppliers of the cryogenic refrigerators.

REFERENCES

1.Riedl,R et al. Design and integration of the FZK cryopump, CCNB Meeting Padua June 5-2003