EU DEMO CRYOGENIC SYSTEM AND CRYODISTRIBUTION Pre-conceptual design for an optimal cooling of the superconducting magnets and the thermal shields

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Pre-conceptual design for an optimal cooling of the superconducting magnets and the thermal shields

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Abstract

With the construction of ITER in progress, the European demonstrator of a fusion reactor plant (EU DEMO) would be a device with lies between ITER and a commercial power plant able to demonstrate the production of electricity and the operation in a closed fuel cycle. CEA has been involved in the EU DEMO pre-conceptual design of the superconducting magnets, of the cryogenic system and the cryo-distribution. In the framework of the EUROfusion collaboration, significant engineering and technological results have come out and paved the way towards the conceptual design of the cryogenic users and the associated cooling system. The nominal design parameters of the cryogenic system for the superconducting magnets at around 4.5 K, for the High Temperature Superconducting Current Leads at about 50 K and for the thermal shields at about 80 K, have been varied (temperature, pressure, mass flows) to study their impact on the refrigerator concept and the helium distribution to the cryogenic users. This design methodology, which was not conducted for previous cryogenic systems (K-STAR, JT-60SA, ITER), is an innovative approach to find an optimized process. It relies on the interactions between designers, cryogenic experts and industry to explore potential ways to optimize the overall cryo-magnetic system including the superconducting magnets and the thermal shields. The preliminary specifications of the future cryogenic system and the cryo-distribution have led to the estimation of the overall refrigeration requirement of around 100 kW equivalent at 4.5 K. After trade-off studies on several process options, one baseline solution has been detailed, using a novel pre-cooling refrigeration with a He-Ne mixed gas cycle. This option enables a potential gain in terms of efficiency of about 5% compared to conventional helium process of large cryoplants. The maturity of the technologies and the R&D strategy are discussed with industry.

1. INTRODUCTION

The Pre-conceptual Design Reports of the EU DEMO tokamak have been reviewed by the project in 2020 to nurture the coming conceptual design studies which will select the baseline engineering designs for the EUropean DEMOnstrator of fusion reactor. The pre-conceptual study elaborated the design of the European demonstrator in the framework of the EUROfusion consortium collaboration [1,2]. To achieve the demonstration of the production of electricity and the operation of the closed fuel cycle, key fusion technologies have to be developed and integrated into the tokamak. Among them, the NbSn3 and Nb-Ti superconducting magnets require the development of large-scale cryogenic system down to 4 K, which also cool down other cryogenic users such as the high temperature superconducting current leads at about 50 K and the thermal shields at about 80 K. For that purpose, an exploratory engineering study was performed with the involvement of industry at an early stage of design activities. The present paper describes the main outcomes of the Air Liquide study.
In the preliminary specification, the cooling requirements have not been fixed to allow interactions between the magnet designers, the cryogenic process engineers and industry to discuss about the optimal cooling parameters at the interfaces (temperature, pressure, mass flows) in terms of overall integrated system, with cost effective solutions for both capital and operation expenditures [3]. This design methodology, which was not conducted for previous cryogenic systems (K-STAR, JT-60SA, ITER), is an innovative approach, based on a review of the common cooling requirements with a larger range of the variables. The optimization relies mainly on minimization of the overall equivalent refrigeration load, and hence the electrical consumption, still maintaining acceptable

temperature margins for the superconducting conductors. Integrated modelling tools [4] (thermal hydraulic, cryogenics, thermal-mechanics, electromagnetic) and iterative calculations were developed to assess the cooling requirements. Trade-off process options have been studied to meet the cooling requirements for the nominal operation, but also for the off-design modes (cool down and turndown operation with reduced refrigeration loads). The expected performances of the cryogenic system have been estimated in terms of efficiency and total electrical consumption. Finally, one of the main results of the study is the conceptual design of the baseline solution, highlighting a novel pre-cooling refrigeration with mixed He-Ne gas cycle. The selection of this architecture allows a potential gain in terms of efficiency of about 5% compared to conventional helium process for large cryoplants. The resulting preliminary general layout is of primary importance for engineering aspects and integration plant for EU DEMO reactor. The maturity of the technologies and the R&D strategy to supply a reliable and sustainable cryogenic system are discussed with industry.

2. REVIEW OF THE REQUIREMENTS

2.1. Preliminary specifications

The overall scope of the cryoplant and cryo-distribution is defined in Fig. 1, together with the process boundary of the exploratory study by Air Liquide. The study included the layout in the cryogenic building and the tokamak hall up to the auxiliary cold boxes (ACBs). The cryodistribution from the ACBs to the cold terminal boxes have been excluded from the study. The main cryogenic requirements in nominal mode are summarized in Table 1 with an estimated heat loads based on assumptions of DEMO 2015 [1,2]. The heat loads include nuclear heating, thermal radiation and conduction loads for the structures, nuclear heating, and thermal radiation and AC losses for the coils. The requirement did not include any heat load for cryopumps (divertor, NBI system), as they may need to be realized by different means in EU DEMO.

The table features ranges of values for the mass flows, the supply temperatures and pressures, with allow industry to explore a broader range of process variants and hence to work out proposals for more flexible and efficient architectures. For the magnets and the structures, the supply temperature range has been enlarged from 4 K to 4.6 K, the supply pressure was set to a maximum of 10 bar, and the pressure drop along the conductor length (several hundred meters) was set to a maximum of 1 bar. One has to bear in mind the conventional values of 4.4 K supply temperature, 5 bar supply pressure and 1 bar pressure drop for the coils of ITER and JT-60SA [5]. For the Thermal shields, the supply temperature was investigated from 60 to 150 K.

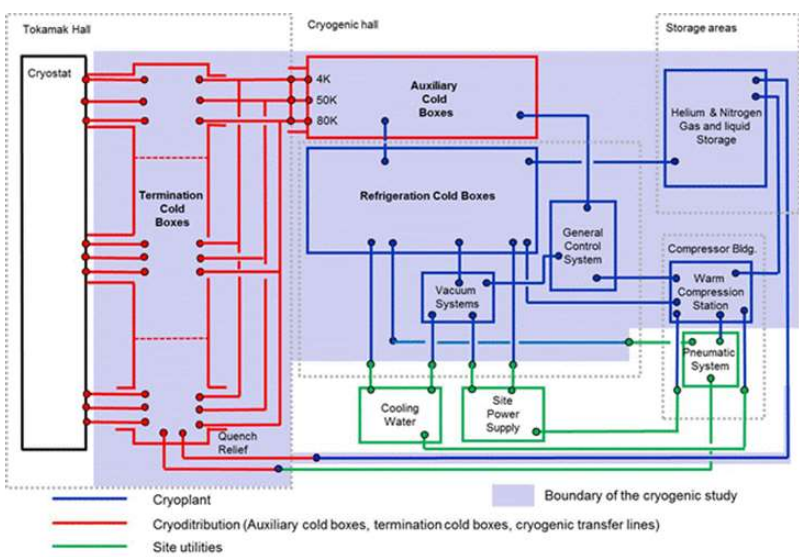


FIG. 1. Scope of study of the cryogenic system and cryo distribution of EU DEMO

TABLE 1. MAIN COOLING REQUIREMENTS FOR EU DEMO CRYOGENIC SYSTEM IN NOMINAL MODE

Cryogenic users	Loads (W)	Mass flows (g/s)	Supply Temperature (K)	Supply Pressure (bar)	Pressure drops (bar)
Toroidal Field coils TF	3200	[1000-3000]	[4.1- 4,6]	[4,10]	<1 bar
Central Solenoid CS	5200	[1600-3100]	[4.1- 4,6]	[4,10]	<1 bar
Poloidal Field coils PF	3200	1600	[4.1- 4,6]	[4,10]	<1 bar
Structures	13900	2700	[4.1- 4,6]	[4,10]	<1 bar
HTS	n.a	250	[48-52]	[4-6]	<3 bar
Thermal shields	1400000/ 590000	13200	[60-150]	[15-20]	<1 bar

2.2. Exergetic analysis

For the conventional cooling parameters, the estimation of the overall refrigeration loads for EU DEMO cryogenics users is around 100 kW equivalent at 4.5 K as shown on Fig. 2 (left), with a large contribution of the 80 K loads for the thermal shields of 64%. This high heat load is a result of a preliminary assumption that the vacuum vessel would always be kept at 473 K to avoid extra baking. If the vacuum vessel would, instead be kept at 373 K, the heat loads for the thermal shields would reduce to 48% of the total equivalent cryogenic loads. The cooling of the superconducting magnet accounts for 28%, half of it is needed for the cooling of the Structures. The second half is shared between the Toroïdal Field (TF) coils, the Central Solenoid (CS) and Poloidal Field (PF) coils. Pressure drops (assumed to be 1 bar for each coil family) have an important impact, as they count for 15% of the overall exergetic demand. The estimated refrigeration requirement is larger than any existing cryogenic plants for fusion as illustrated on Fig. 2 (right), with a major contribution of the thermal shield loads.

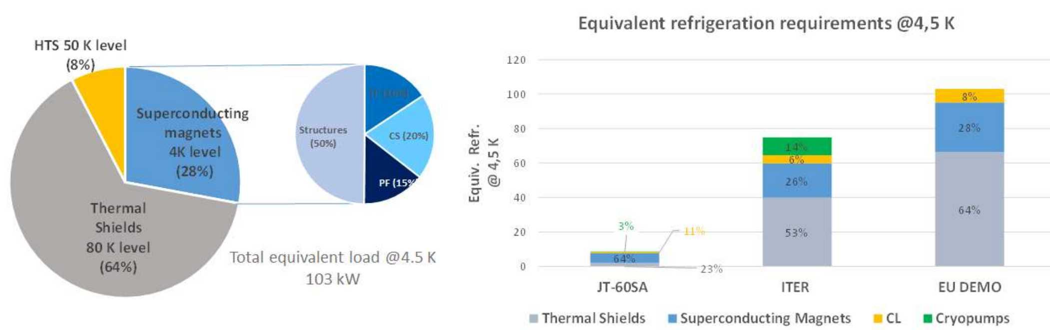


FIG. 2. Total exergetic load distribution among the EU DEMO cryogenic users (left) and EU DEMO equivalent refrigeration requirements @4.5 K compared to JT-60SA and ITER (right)

2.3. Parametric studies

The main outcome of the review of requirements, by performing parametric studies, was the potential reduction of the electrical power consumption related to the 4 K level refrigeration (-20 %) by:

— Reducing mass flows and pressure drops, lowering the supply temperature to ensure acceptable temperature margin with respect to the current sharing temperature of the conductor design. The “Opti1” case (4.1 K, 5 bar, 0.2 bar pressure drop) and The “Opti2” case (4.6 K, 5 bar, 0.2 bar pressure drop) is illustrated on Fig 3 and is compared to the “Base” case (conventional cooling supply parameters: 4.5 K, 5 bar, 1 bar pressure drop). The potential reduction ranges respectively from 4% to 13% compared to the “Base case”.

— Increasing the supply pressure of the magnet SHe cooling loops: A higher supply pressure leads to lower pressure ratio in the circulator and thus decreasing the pumping power. Moreover, the pressure drops would also decreased.

— Decreasing the SHe supply pressure to a minimum value of 2.5 bar to keep margin with respect to the critical pressure of 2.3 bar: it allows a gain in the enthalpy drop across the cold end turbine. Besides, the isenthalpic expansion through the JT-valve generates less "flash" vapour to the phase separator.

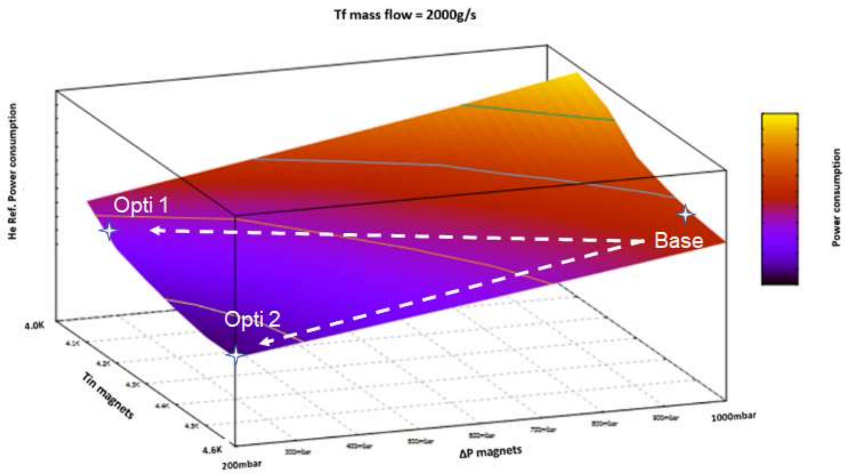


FIG. 3. Electrical power consumption related to TF refrigeration loads versus supply temperature and pressure drops in the Toroïdal Field Coil cooling loop. For a given TF mass flow of 2000g/s, the 3D plot shows the variation of 2 parameters (supply temperature and pressure drop) on the electrical consumption related to the 4 K loads (the colored lines correspond to cases with an equal electrical power consumption)

3. TRADE-OFF STUDIES ON THE DESIGN ANALYSIS AND ON THE PERFORMANCE

3.1. Optimal refrigeration requirements

Based on the review of the requirements and the parametric studies, a set of cooling requirement have been selected to perform trade off studies on several cryoplant and cryo-distribution architectures and are summarized in Table 2.

TABLE 2. OPTIMAL REFRIGERATION REQUIREMENTS IN NOMINAL MODE

Cryogenic users	Loads (W)	Mass flows (g/s)	Supply Temperature (K)	Supply Pressure (bar)	Pressure drops (bar)
Toroidal Field coils TF	3200	1500	4.1	15	0.3
Central Solenoid CS	5200	1500	4.1	15	0.3
Poloidal Field coils PF	3200	1500	4.1	15	0.3
Structures	13900	1500	4.1	15	0.3
HTS	n.a	250	50	3	1 bar
Thermal shields	590000	13200	90	15	1 bar

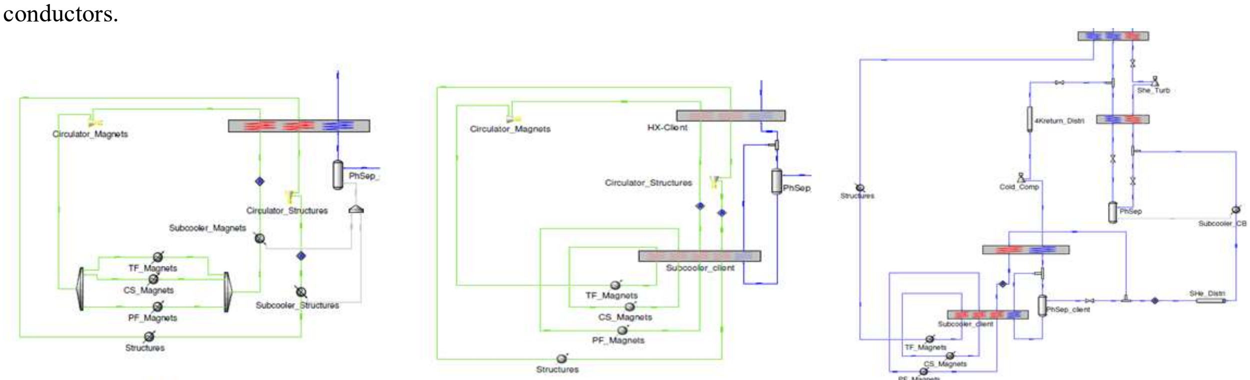
3.2. Process study at the 4 K level

Three different distribution schemes at the 4 K supply level have been investigated:

- The ITER-like distribution scheme is a conventional scheme with independent SHe loops for each magnet family and for the Structure (Fig 4.a).
- The multi-pass distribution a non-conventional scheme, featuring an arrangement of the magnet families (TF, CS and PF) with cooling circuits in series and with multi-passes to the sub-cooling heat exchanger (Fig. 4.b).

– The Direct supply from the main cycle was shown to become thermodynamically relevant if the total mass flow to the magnets is significantly reduced.

The two last distributions schemes are possible with lower mass flows and pressure drops and can lead to potential reduction of the power electrical consumption. However, at the conceptual design phase, thermal hydraulic analysis should be performed to investigate these distribution schemes and check the temperature margin of the conductors.



(a) « ITER-like »
Independant magnet and structure loops

(b) « Multipass » loop with magnet in series and structure loop

(c) « Direct supply from the main cycle »

FIG. 4. Cryo-distribution scheme proposals to investigate architecture with lower mass flows and pressure drops for SHe cooling loops

3.3. Precooling options at 80 K level

2 different pre-cooling variants have been compared:

– ITER-like with LN2 precooling: The secondary cycle with pure LN2 is powered by 6 centrifugal compressors and operates from 300 K to 80 K.

– Mixed gas (He+Ne) precooling: the secondary cycle with helium (70%) and a neon (30%) is powered by 5 centrifugal compressors and operates from 300 K to 70 K. The main benefit of this mixed gas with higher density than pure helium is to increase the compression factor of the centrifugal compressor (from 1.2 to 1.4), allowing a higher compression for the same radial wheel speed. The neon fraction is of 30% is a good compromise between the number of compression stages and the higher mass flow rates in the cold box due to the lower heat transfer properties of neon compared to pure helium.

At the 4 K level the process architectures are similar and the main difference is the warm compressor technologies for the second stage compressor MP/LP. Both have primary pure helium cycle. In the ITER-like architecture, helium has a first and a second stage of screw compressor whereas the He +MR cycle features a second stage with 8 centrifugal compressors.

For both secondary cycle, a pure gaseous helium forced flow driven by a cold circulator exchanges the heat from the thermal shield with the LN2 or [He+Ne] pre-cooling cycle. A trade-off study between cold and warm circulators have shown that cold circulator allows a more efficient cycle if the thermal shields have lower pressure drop than 1 bar. Moreover the heat exchangers would be much smaller with a cold circulator.

The main drawback is the cool down capacity which could be limited with a cold circulator compared to a warm circulator with a bigger capacity. For both LN2 and [He+Ne] precoolings, the warm turbines will be powerful enough (>100 kW) to use a power recovery system (PR).

Table 3 summarizes the electricity power consumption and Carnot efficiency of the two process architectures. The [He +MR] cycles would reduce the electricity consumption of about 17%, with an increase of the Carnot efficiency of about 4%. With power recovery system, the additional reduction of electricity consumption is about 6% and the Carnot efficiency is further increased of 3%, leading to a Carnot efficiency of 31%.

The other advantage of the mixed gas precooling is the flexibility of this process scheme compare to a LN2 precooling with a fixed temperature for the phase separator at 77 K. The gas mixture composition can be chosen accordingly to the supply temperature needed for thermal shields, depending of the thermal-hydraulic requirements.

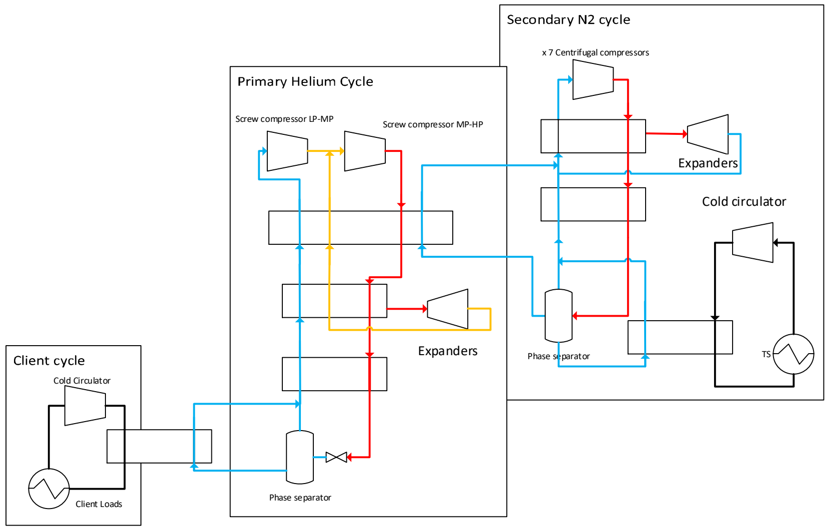


FIG. 5. [He-LN2] ITER-like Process architecture with LN2 pre-cooling

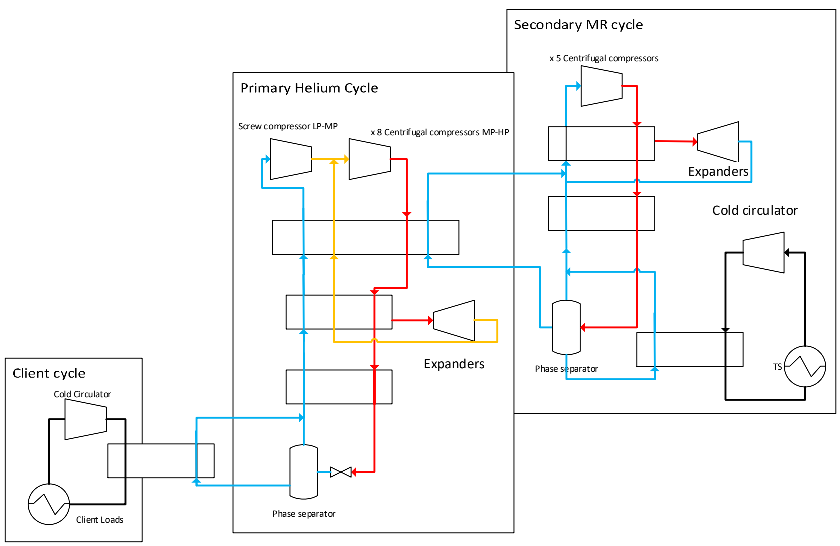


FIG. 6. [He+MR] Process architecture with [He-Ne] pre-cooling

TABLE 3. ELECTRICAL CONSUMPTION AND CARNOT EFFICIENCY FOR TWO PRE-COOLING OPTIONS (LN2 AND MIXED REFRIGERATION)

Options	Pre-cooling	Electrical consumption (%) without PR	Carnot Efficiency (%) without PR	Electrical consumption (%) with PR	Carnot Efficiency (%) with PR
ITER-like –[He-LN2]	LN2	100	25	94	26.
[He +MR]	He+Ne	83	29	76	31

4. CONCEPTUAL DESIGN: MIXED REFRIGERATION AND HELIUM CYCLES

Based on the trade-off study, the helium and [He +Ne] cycles were selected as a baseline process architecture to be further detailed in a conceptual design study. The conceptual design was based on two refrigerator units running in parallel, each unit taking half of the loads. This arrangement allows robustness to the cryogenic system (Fig. 7). Below 70 K, one helium refrigeration cycle provides 50 K and 4 K refrigeration for the current leads and for the superconducting magnets in a conventional Claude cycle with turbo-expanders. Above 70 K, a mixed refrigerant (MR) plant using a mixture of neon and helium and centrifugal compressors provide the refrigeration capacity for the thermal shields at around 80 K.

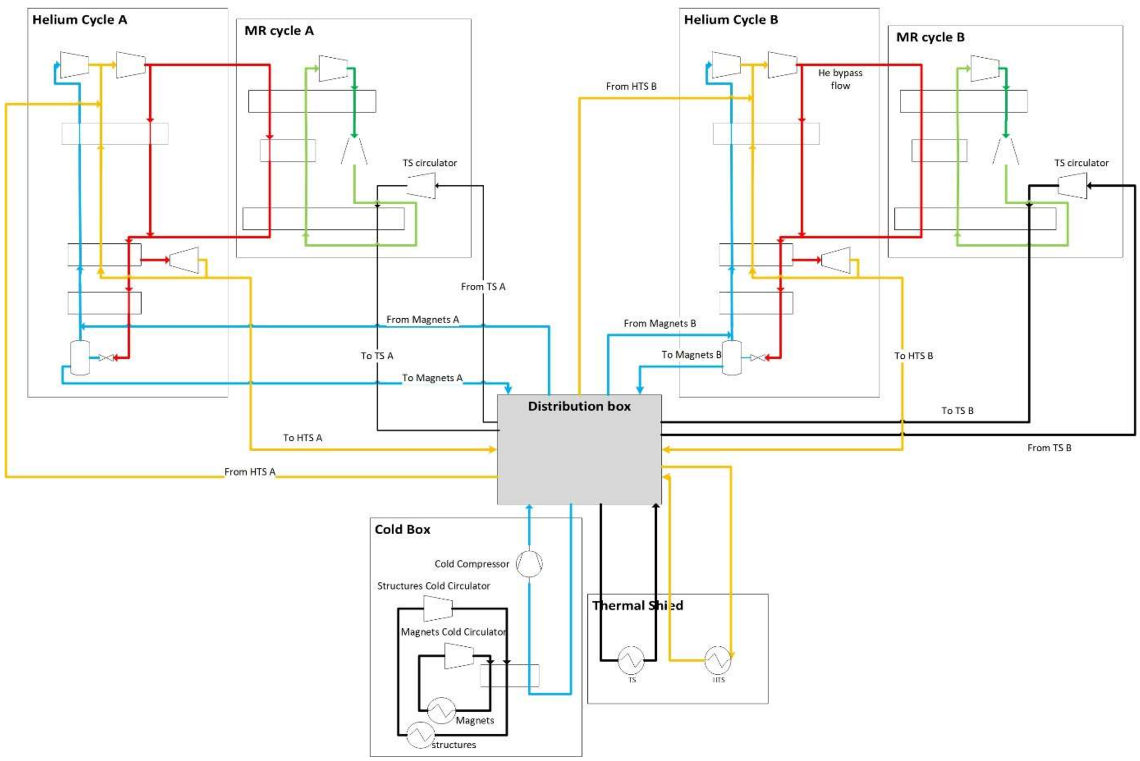


FIG. 7. General process scheme: Helium and Mixed gas cycles

The preliminary layout in the cryogenic building is presented in Fig. 8 with the warm He screw compressors and their oil removal systems, the He centrifugal compressors and the [He+ Ne] centrifugal compressors, the two helium cold boxes and the two [He+ Ne] cold boxes, the distribution box and the main transfer line towards the tokamak hall.

For the EU DEMO exploratory study, the ACBs are considered to be located inside the Tokamak building, at the closest possible location to the cryogenic users. This configuration allows to have a single cryoline between the Cryoplant building and the Tokamak building. This location leads to an optimal solution in terms of heat loads and total length of the cryolines. However, to minimize the number of components in the tokamak hall, which have to meet stringent safety requirements, the option of having the ACBs in the cryogenic building need to be investigated in the future. From a cryogenic point of view, increasing the distance would increase the overall capacity of the cryogenic system due to the additional loads, pressure drops related to the additional lengths of the cryogenic lines

The technology maturity of the components of the He+MR cycles has been discussed with industry. The conceptual design for the compression of the MP/LP helium cycle and the MR cycle warm is an advanced technology allowing oil-free helium compression with high-speed turbo-centrifugal compressors as alternative solution to screw compressors. This advanced technology is already commercially available and currently used in other applications such as Turbo-brayton systems. It offers larger flow capacities and better efficiencies than the screw compression reducing the overall power consumption by about 17% (Table 3). The technical challenge of this advanced technology is to limit the losses of process gases (Ne or He) during compressor operation, keeping an optimized Efficiency/Cost ratio. Developments are needed to extend the current product range and to develop a shaft sealing process limiting the volume of Helium lost or to be purified. Concerning turbine energy recovery, investigations would be carried out on electrical generation and last stage of centrifugal compression (booster) or combination of the two. Adapted to turbine shaft powers larger than 100 kW, it would improve the Carnot efficiency of about up to 3% (Table 3).

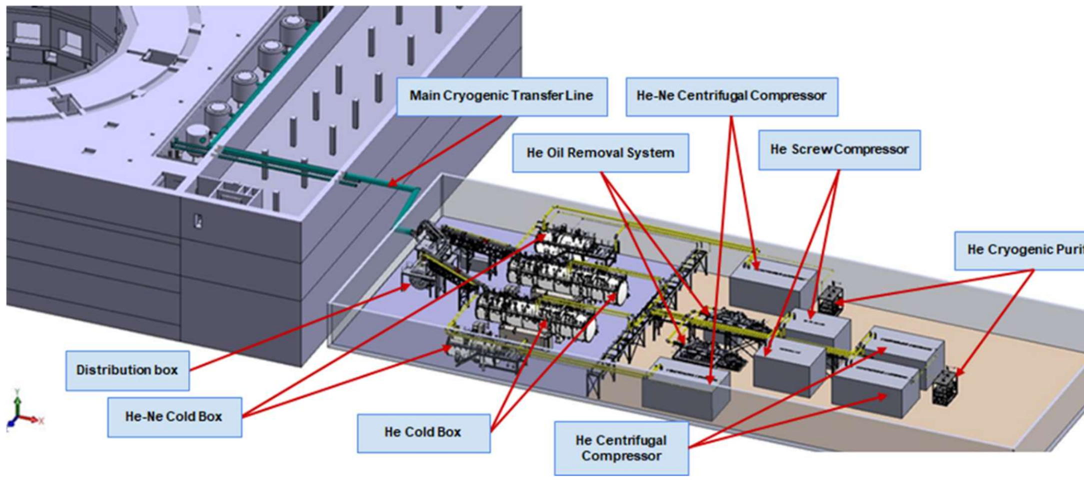


FIG. 8. Preliminary layout of the cryogenic building for EU DEMO cryogenic system and cryo-distribution

5. CONCLUSION AND PERSPECTIVES

The involvement of industry at the early stage of the pre-conceptual design is an innovative approach to the anticipated cooling requirements and to identify some paths of investigations for novel process architectures at the 4 K and 80 K levels. Trade-off studies led to compare two process solutions: ITER-like [He+LN2] or Mixed Refrigeration and helium cycles [He+MR]. The Mixed refrigeration and helium cycles offers better efficiency and flexibility in the range of 60-150 K for the thermal shield cooling and the precooling of the helium cycle. The conceptual design of the Mixed Refrigeration cycles led to an estimated Carnot efficiency of 31%, thanks to the use of mature advanced technologies based on centrifugal compressors and turbine recovery systems.

ACKNOWLEDGEMENTS

This work has been carried out within the framework of the EUROfusion Consortium for the EU-DEMO work package WPPMI. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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