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CHALLENGES FOR CRYOGENICS AT ITER

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ABSTRACT

Nuclear fusion of light nuclei is a promising option to provide clean, safe and cost competitive energy in the future. The ITER experimental reactor being designed by seven partners representing more than half of the world population will be assembled at Cadarache, South of France in the next decade. It is a thermonuclear fusion Tokamak that requires high magnetic fields to confine and stabilize the plasma.

Cryogenic technology is extensively employed to achieve low-temperature conditions for the magnet and vacuum pumping systems. Efficient and reliable continuous operation shall be achieved despite unprecedented dynamic heat loads due to magnetic field variations and neutron production from the fusion reaction.

Constraints and requirements of the largest superconducting Tokamak machine have been analyzed. Safety and technical risks have been initially assessed and proposals to mitigate the consequences analyzed. Industrial standards and components are being investigated to anticipate the requirements of reliable and efficient large scale energy production.

After describing the basic features of ITER and its cryogenic system, we shall present the key design requirements, improvements, optimizations and challenges.

KEYWORDS: Large scale refrigerator, cryogenic distribution, supercritical helium, cold compressor, superconducting device, fusion.

INTRODUCTION

ITER [1] (originally an acronym for International Thermonuclear Experimental Reactor), has been designed to demonstrate the scientific and technical feasibility of nuclear fusion as a primary source of virtually inexhaustible energy. It is now entering the procurement and construction phase at Cadarache, South of France (FIGURE 1 and FIGURE 2). It is the world's biggest fusion energy research project, and one of the most challenging and innovative scientific endeavor in the world today.

FIGURE 1. Status of the ITER construction site at Cadarache in April 2009.

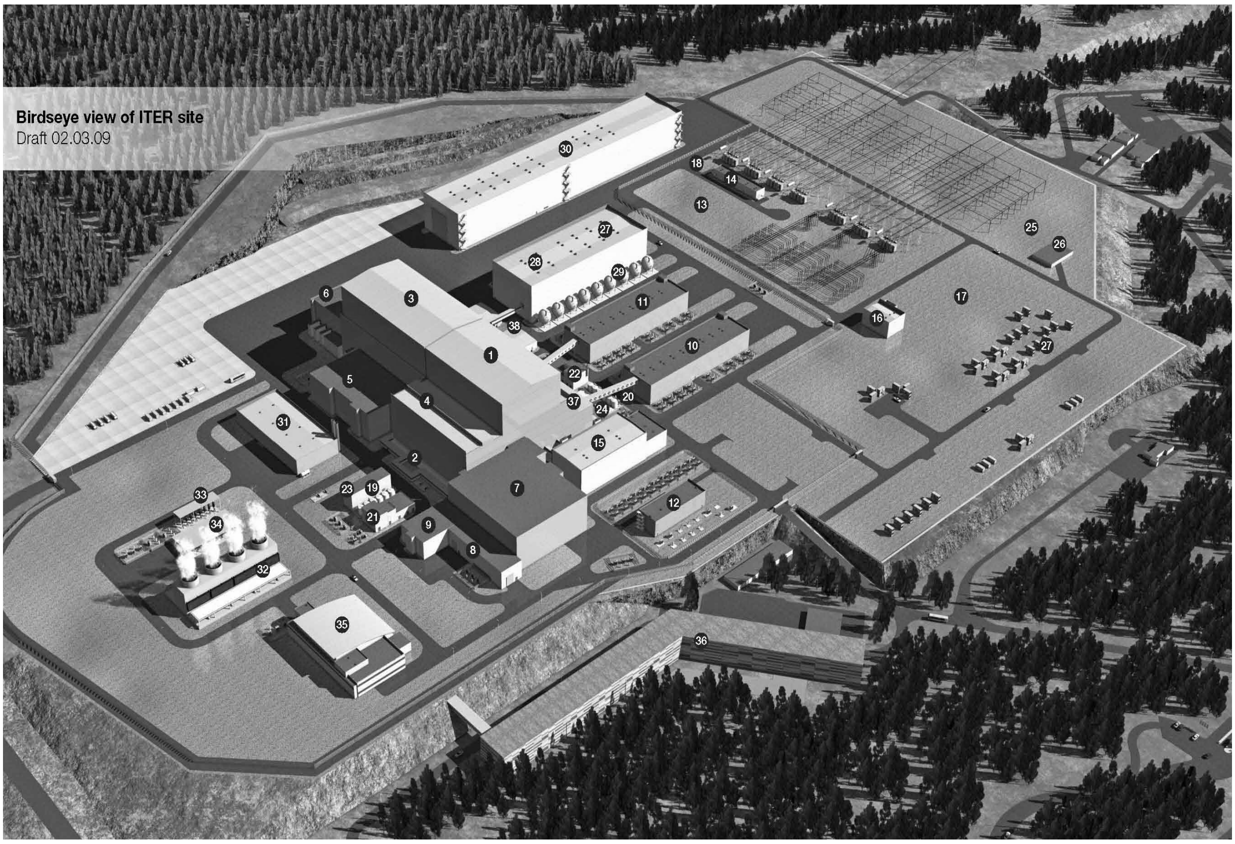

FIGURE 2. ITER Project site layout: 3-D graphics view.

Fusion power

Energy and global warming are two of the main issues for the world today. The need for energy and the effect on the global warming is especially true for developing countries. Today fossil fuels provide about 80 % of our energy needs. The main concerns are that these resources are finite (about 50 or 100 years depending on the growth of the population and energy consumption [2]) and the increasing CO_2 production may cause irreversible climate changes. Together with an improved efficiency in energy production and distribution (for which cryogenics and superconductivity can take an important role) we need to establish a medium and long-term strategy. Energy options are renewable (solar, wind, etc.), nuclear fission (with new generation reactors) and fusion. There is no silver bullet and the solution would require all available sources to ensure progress and development for all countries.

Fusion is an attractive source of energy because fuel is abundant and distributed world-wide. There is sufficient deuterium in seawater for millions of years. Tritium is produced by lithium (available in seawater) or from conservative lithium ore recovery that is estimated to provide a supply for thousands of years [3]. Fusion machines are intrinsically safe as the reactor contains fuel for only a few seconds burn. Fusion waste is not a long-term burden as it attains low radio-toxicity after less than 100 years.

Fusion is the energy source which powers the sun and the stars. Hydrogen is burned to helium at a temperature of 15 million deg C (plasma) and is confined by gravitational forces. On earth we would burn together deuterium and tritium at 100 to 200 million deg C and confine the plasma by magnetic fields created by large superconducting magnets and current induced in the plasma itself. Fusion of deuterium and tritium will produce helium and high energy neutrons slowed down in a lithium blanket to extract power (500 MW for ITER, 1-2 GW for future machines) and breed new tritium fuel for the reactor.

The ITER Project

The idea for ITER originated from the Geneva Superpower Summit in 1985 where Gorbachev and Reagan proposed an international effort to develop fusion “as an inexhaustible source of energy for the benefit of mankind”. Several years later, on the 21st of November 2006, China, Europe, India, Japan, Korea, the Russian Federation and the United States of America signed the ITER agreement.

ITER overall programmatic objective is to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes. The principal goal is to produce significant fusion power amplification (tenfold the energy input).

The machine cost would amount to 5.5 billion € for ten years of construction and 5.5 billion € for 20 years of operation and decommissioning. The ITER organization is a truly international cooperation where the seven parties involved in the construction represent more than 50 % of the world’s population. The execution and procurement of components will be based on 90 % of in kind contributions from the seven member parties.

Cryogenic components and equipment will be procured from China, the European Union, India, Korea and the United States of America. The ITER Organization in Cadarache is responsible to define the conceptual design, coordinate and integrate the work of the Domestic Agencies, commission and operate the machine. In addition the ITER Organization in Cadarache will directly procure the liquid helium refrigerators from one of the 7 parties.

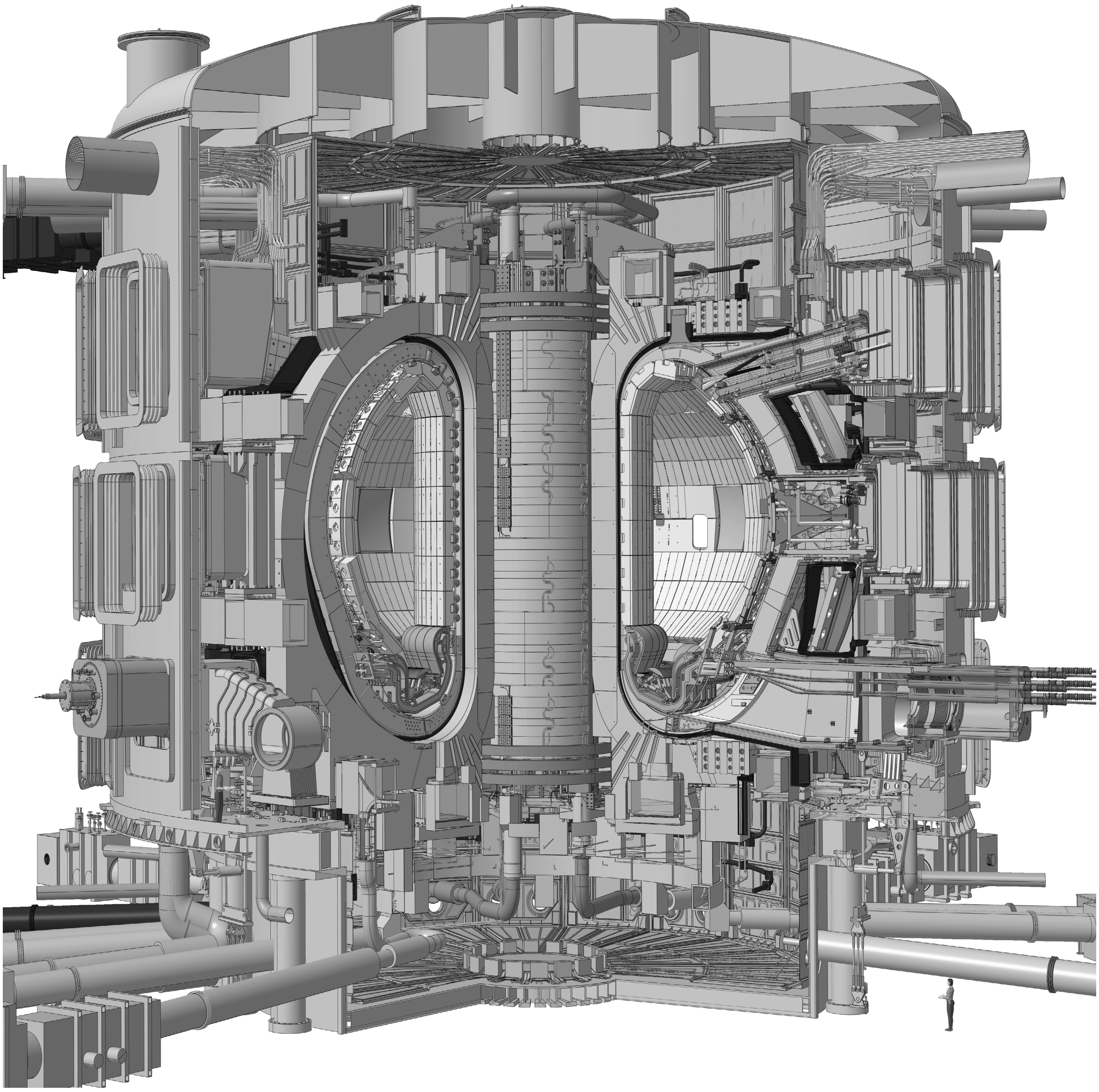

FIGURE 3. The core of the ITER machine.

Main components

The ITER machine (FIGURE 3) requires high magnetic fields to confine and stabilize the plasma. The magnet system [4] is made up of 18 Toroidal Field (TF) coils, a 6-module Central Solenoid (CS), 6 Poloidal Field (PF) coils, 9 pairs of Correction Coils (CC) and High Temperature Superconducting Current Leads made of Ag-Au BiSCCO 2223. The TF coils field confines the charged particles in the plasma. The CS coils provide an inductive flux to ramp-up and drive the plasma as well as giving shape and vertical stability. The PF coils field provides radial position equilibrium of the plasma with shaping and vertical stability. The CC coils correct error fields harmonics.

The magnets are made of Circular Cable in Conduit conductor with about 1000 strands, Nb3Sn for CS, TF, and NbTi for PF and CC. The magnets require cooling with supercritical helium at an inlet temperature of 4.2 to 4.5 K and the possibility of enhanced cooling at 3.8 K.

All magnets are surrounded by a large cylindrical cryostat and an actively cooled silver-coated thermal shield.

Cryogenics is also required for the evacuation of the cryostat insulation vacuum and the Torus vacuum as well as the pumping of the fusion reaction ashes (deuterium, tritium and helium) for processing in the tritium plant. Large cryosorption panels are used to achieve high pumping rates and vacuum levels [5].

DUTIES AND CONSTRAINTS

The ITER cryogenic system [6, 7] is designed to guarantee stable operation for the magnets and cryopumps over a wide range of plasma scenarios ranging from short (few hundred seconds) plasma pulses with enlarged fusion power (700 MW) to long plasma burn times of 3000 seconds and fusion powers of 365 MW.

The key design requirement is to cope with large dynamic heat loads deposited in the magnets due to magnetic field variation and neutron production from deuterium-tritium fusion reaction. At the same time the system must be able to cope with the regular regeneration of the cryopumps to 80 K as well as higher temperature regeneration at 470 K.

The basic duties of the cryogenic system are the cooldown of the cryopumps in order to pump the cryostat and torus and the gradual cooldown and fill of the magnet system and thermal shields. Once at nominal operating temperatures, the cryogenic system has to maintain the magnets and cryopumps at these operating conditions over a wide range of operating modes. It has also to accommodate resistive transitions and fast discharges of the magnets and limit the time to recover back to nominal operating conditions. Additionally the cryogenic system must ensure high flexibility and reliability of operation together with low maintenance requirements.

ARCHITECTURE

The ITER cryogenic system consists of two main sub-systems (FIGURE 4 and 5): the cryoplant [8] and the cryodistribution [9].

The cryoplant is composed of helium and nitrogen refrigerators combined with an 80 K helium loop. Storage and recovery of the 24 t helium inventory is provided in warm and cold (80 K) gaseous helium tanks.

Three helium refrigerators will supply the required cooling power via an interconnection box providing interface to the cryodistribution system and redundancy of operation between refrigerators during faulty scenarios. One of the helium refrigerators is fully dedicated to the cryopump system for the cooling of the cryopumps prior to cooling the cryostat. It accommodates regular variations of liquefaction and refrigeration loads for cryopumps operation. The other two refrigerators are used for the magnets system and provide partial redundancy for stand-by operation while keeping the refrigerator size within industrial standards.

Two nitrogen refrigerators provide cooling power for the thermal shields and HTS leads cooling as well as 80 K pre-cooling of the helium refrigerators.

The cryogenic distribution system is composed of:

- the main cryogenic distribution boxes (ACB),
- a complex system of cryogenic transfer lines located inside the Tokamak building, in the cryoplant buildings and in between the two buildings,
- the cold termination boxes for the magnet system (CTB),
- the cold valve boxes for the cryopumps and the thermal shields (CVB).

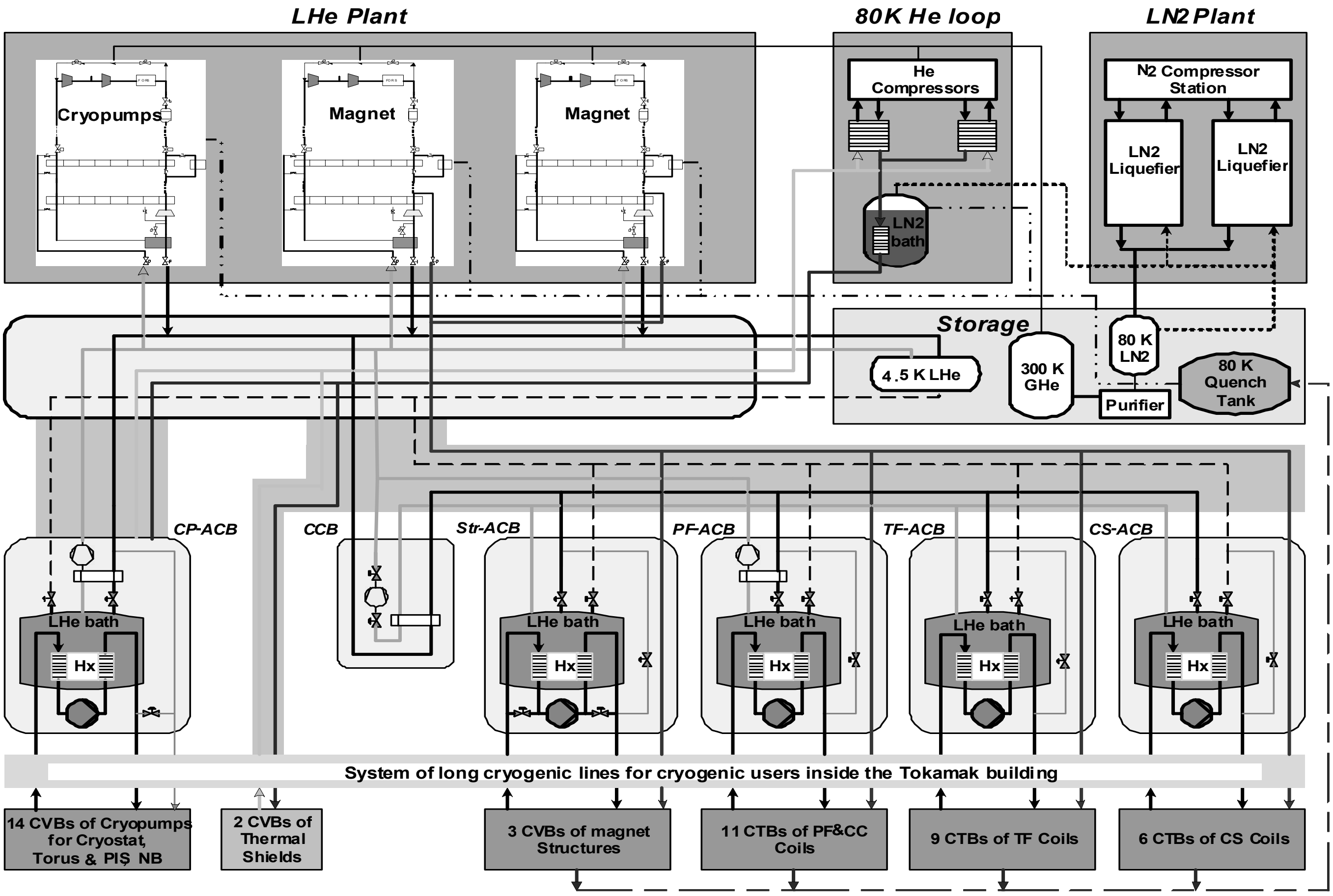

FIGURE 4. Architecture of the ITER cryogenic system.

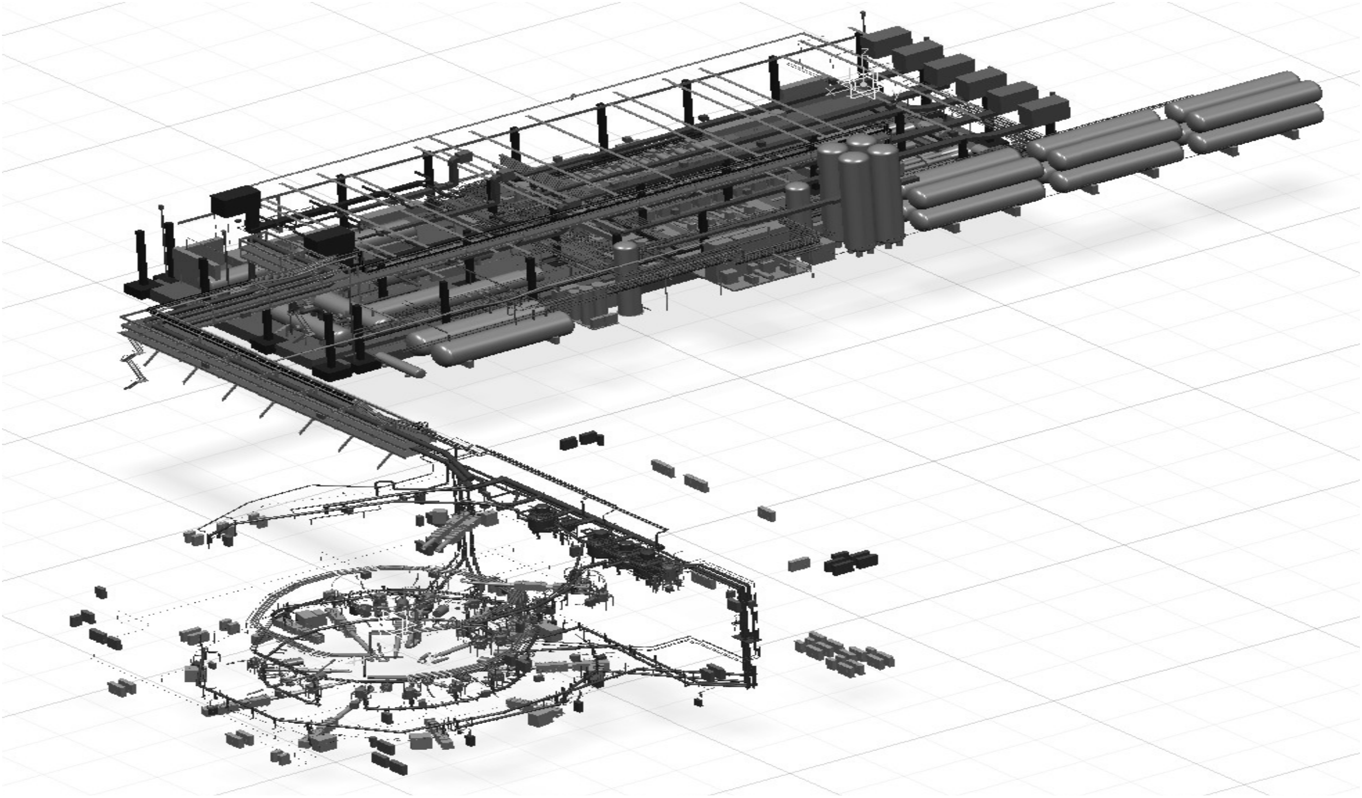

FIGURE 5. 3-D virtual view of the cryogenic system.

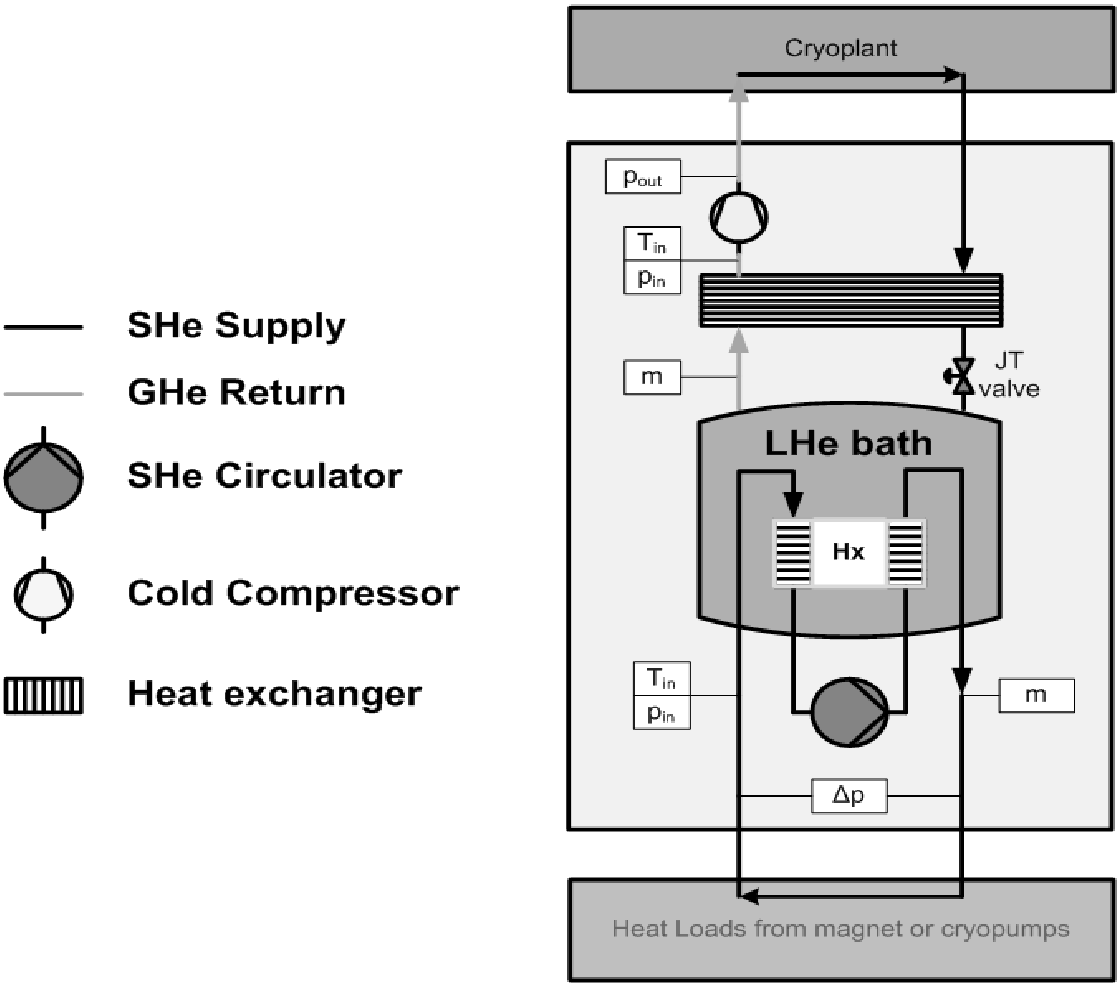

FIGURE 6. Magnets and cryopumps cooling scheme.

COOLING SCHEME AND CRYODISTRIBUTION

The distribution of cooling power is provided via a complex system of cryolines with a total developed length of 3 km and 50 cryodistribution boxes. The cooling scheme is shown in FIGURE 6.

Supercritical helium circulating pumps are installed in each ACB for forced flow cooling of magnets and cryopumps. The heat loads from the users and the circulating pump are extracted via a heat exchanger immersed in the helium bath. The heat exchanger is divided in two parts to fix the required operating temperature at the inlet and outlet of the circulating pump. Mitigation of the heat load to the helium refrigerators can be performed by-passing the heat exchanger of the Structure making use of its high thermal inertia. The structure normal operating temperatures are recovered during the plasma dwell time before the next shot.

Cold compressors are used to lower the operating temperatures. A common cold compressor is shared for the Structure, the CS and the TF coils. Dedicated cold compressors are used for the cryopumps and the PF coils due to the different requirement in operating temperature. A heat exchanger located upstream of the cold compressor reduces the JT flash into the helium bath.

The cold termination and valve boxes (CTB, CVB) are the front-end cryogenic distribution interfaces to the magnets, cryopumps and thermal shields (FIGURE 7 and 8).

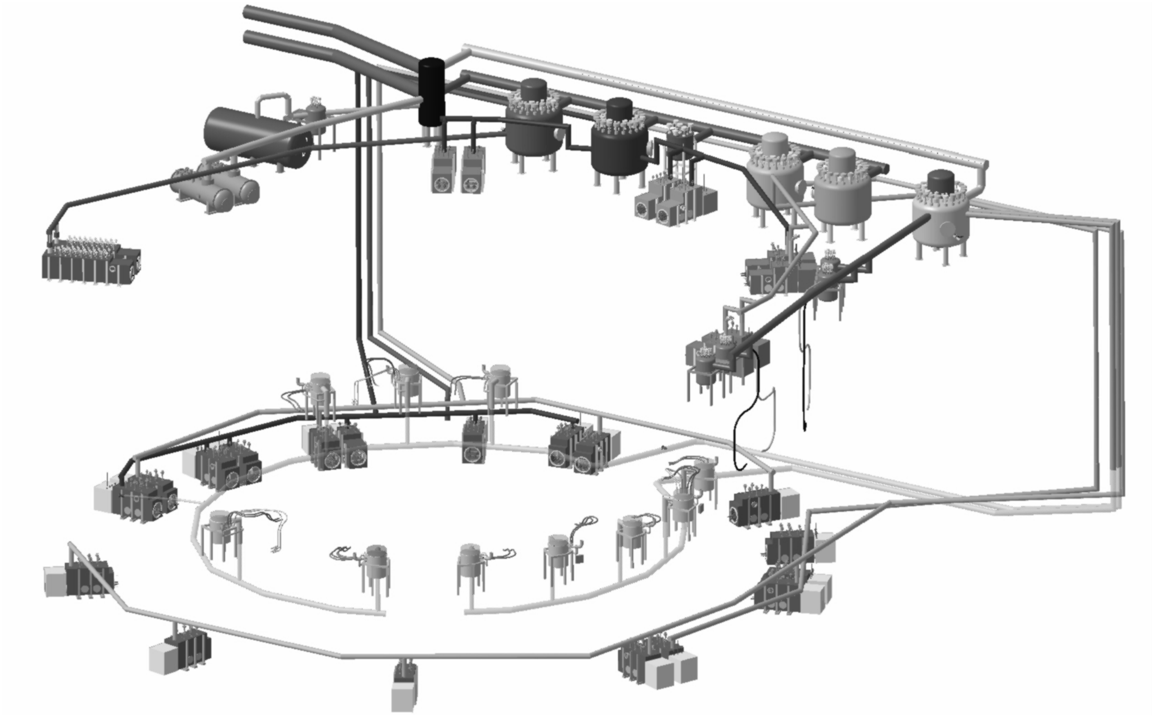

FIGURE 7. Cryogenic distribution layout and front-end cryogenic boxes.

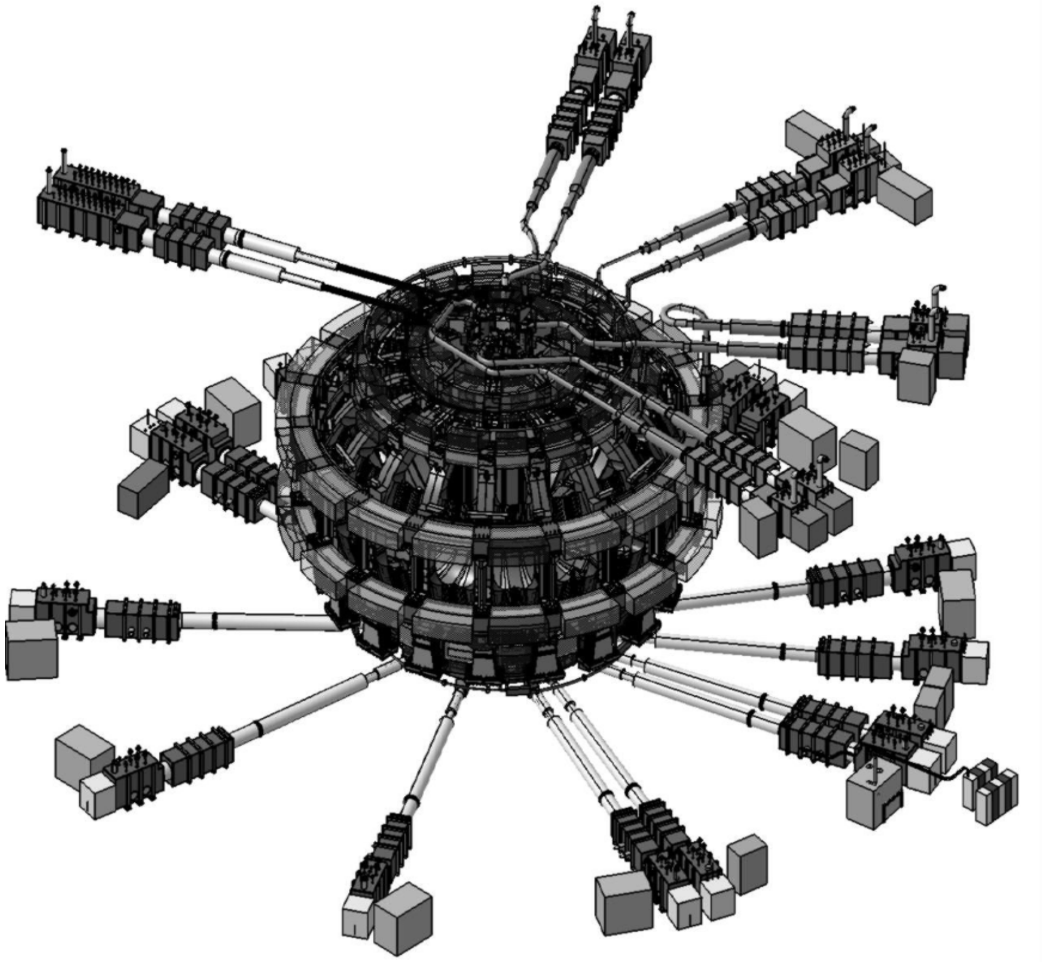

FIGURE 8. Layout of magnets termination boxes in the Tokamak building.

A large network of warm and cold pipe inside the Tokamak building is deployed to recover helium from quench magnets, safety valve relief and current leads return at ambient temperature.

HEAT LOADS

The cryogenic system provides cooling power at four different temperature levels, namely: 4.2 K, 4.5 K, 50 K and 80 K. All loops will use helium as cryogenic fluid in the Tokamak building.

The recently estimated heat loads to size the cryogenic system are given in TABLE 1. Uncertainty and overcapacity factors are still being adapted to the fast periodic transient scenarios of a fusion machine in order to minimize investment costs while ensuring efficient operation and high reactivity.

The static and dynamic heat loads to establish cryogenic requirements have been recently reviewed and updated. The heat loads and updated requirements for cooling capacity will be staged during the different operating phases of ITER (commissioning, Hydrogen plasmas and full deuterium-tritium operation) to minimize investment costs and validate the machine requirements.

LARGE-CAPACITY POWER REFRIGERATION

Large refrigerators at 4.5 K are required to cope with the requirements and heat loads of the magnets and cryopump systems.

The refrigerators have to cope with static and dynamic heat loads for various plasma scenarios, with large dynamic loads variation and high repetition rates. They have to provide cooling power at 80 K, 50 K and 4.5 K. Liquid nitrogen pre-cooling is available via the nitrogen refrigerator. The 80 K loop decouples the requirements of 80 K cooling with high flow rate for the thermal shield from the helium refrigerator making use of a separate plant. The nitrogen plant cooling power of 1300 MW will also ensure the cooldown of the whole machine in about one month (FIGURE 9).

TABLE 1. ITER heat loads averaged over the most demanding plasma pulsed operation scenario

Type of load	**Temperature level**	**Averaged value**
Nuclear heating	4.2 K	3.1 kW
Variable heat load (AC losses & Eddy currents)	4.2 K	14.8 kW
Static heat loads	4.2 K	12.0 kW
SHe circulating pumps and cold compressors	4.2 K	17.2 kW
Cryopumps system and small users	4.5 K	4.2 kW + 0.1 kg/s
HTS current leads	50 K	0.15 kg/s
LHe plant precoolers	80 K	500 kW
Thermal shields and cryopumps baffles	80 K	800 kW (Baking)

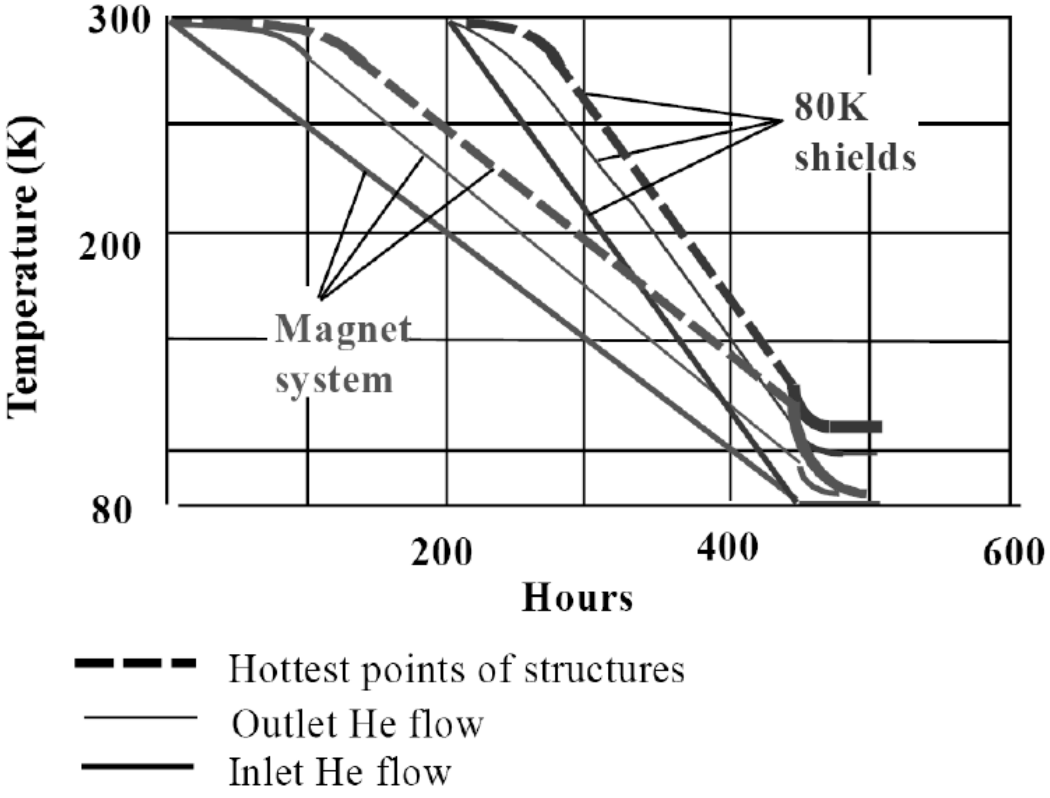

FIGURE 9. Magnet system cooldown.

The refrigerators and the whole cryoplant which comprise the dryers, gas medium pressure storage for 24 t of helium, liquid helium and liquid nitrogen, purification system, will make use of state-of-the-art technology adapted to large dynamic loads and parallel refrigerators' operation. Two large units of about 26 kW for the magnets and a smaller one of 13 kW for the cryopumps and small users will be installed in order to minimize costs and improve efficiency. Staged installation for the various phases of the machine operation will be adopted instead of uncertainty factors and margins. The requirements and loads for the refrigeration system will be therefore constantly checked and validated before committing to an upgrade.

In addition the cryoplant system will be designed to ensure high flexibility and reliability in line with machine operation requirements as well as low maintenance of equipments for reduced shutdowns.

MAIN COMPONENTS AND VALIDATION PROGRAM

The conceptual design proposed and described fully meets the requirements and constraints established for the ITER cryogenic system. The ITER Organization is therefore ready to start direct and indirect procurement (via the ITER domestic agencies) of cryogenic components.

However, technical variants compatible with the requirements and basic design principles are presently under study to simplify the layout and improve performances, reliability and availability.

The large dynamic load handling is under review to optimize the cryoplant and cryodistribution layout and size. Various methods such as pulse mitigation by temporary by-pass of the structure load or variation of the supercritical helium circulators speed, use of liquid helium storage and complex process control for direct handling by the refrigerator are being studied.

The parallel operation of two or three refrigerators as well as the optimal size and number of cold boxes will be studied in order to optimize costs, overall reliability and availability. Dynamic simulators and tests on down-scaled installations will be used to assess the various methods of operation and the process control algorithms.

Developments of technology and engineering solutions are required for some key components such as helium heat exchangers and SHe circulating pumps. Large supercritical helium flow rate handling capability (flow up to 3 kg/s) and turn-down ratio would require some development and testing to verify the performances in the operation ranges of interest and confirm that the expected efficiency of 70 % can be met. Thermodynamic cycle optimization for the large refrigerators could also be further optimized taking into account operating parameters and modes.

Detailed cooldown studies are performed to verify requirements and limitations for the cryoplant sub-system during transient phases.

The safety analysis of the cryogenic system will identify possible areas requiring modification to account for the constraints of a nuclear installation with a large tritium inventory. In particular, that the possible release of helium in the leak tight Tokamak building is compatible with personnel and installations safety. Otherwise an ad-hoc recovery and buffering system is required to reduce the risk of building overpressure, oxygen deficiency and break of secondary containment.

PROJECT STATUS AND PROSPECTS

In June 2009 the ITER Council endorsed as a working basis for further development the proposed phased approach to the completion of ITER construction. To reduce risks, primary components of the machine will be tested before the progressive installation of in-vessel components continues. The target date of First Plasma was confirmed for 2018 and the beginning of deuterium-tritium operation in 2026.

Cryogenics will be installed without contingency and margins with respect to final requirements and heat loads; any upgrade, if needed and validated during commissioning, will be implemented during the first shutdown for in-vessel components installation.

Procurement contracts for cryogenics will be issued between 2010 and 2013. Commissioning will start in 2016.

CONCLUSION

The ITER cryogenic system conceptual design fulfils the requirements and constraints of the largest nuclear fusion installation in the world. It is one of the key components of the future machine and its technological challenge is to prepare efficient and industrially available systems for future reactors.

ITER is a tremendous technical, managerial and scientific adventure exploring and pushing forward the frontiers of our knowledge. Technology developed for Fusion could contribute to solve the greatest challenge to mankind.

Successful collaboration among the ITER Organization, the Domestic Agencies and industry will be a key element for the successful completion of the project.

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The work reported herewith is that of many colleagues from the ITER Organization in Cadarache, the Members of the Organization, as well as partners in industry and contributing laboratories worldwide. I wish to thank all for their contribution.

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