2 Magnet System

2.1 Functions, Basic Configuration and System Boundaries

2.1.1 Functions and Basic Configuration

The magnet system shall be designed to perform the functions described in DRG1.

The magnet system consists of;
- the superconducting toroidal field (TF) coils and associated structures including gravity supports and vacuum vessel supports,
- the superconducting poloidal field (PF) coils and associated structures,
- the superconducting central solenoid (CS) and associated structures,
- the superconducting correction coils (CCs) and associated structures,
- the coil feeders and instrumentation.

All the magnetic field coils are superconducting coils using the "cable-in-conduit" technology and are cooled with supercritical helium at about 4.5K.

Nb_3Sn superconductor is selected for the high field TF coils and the CS (maximum field of 12 to 13.5 T).

NbTi is used for the PF coils and CCs (maximum field about 6 T).

All PF coils and all CCs shall be located outside of the TF coil bore.

The coil feeders are composed of components such as superconducting busbars, instrumentation wires, helium supply and return pipes, control valves, and feedthroughs. The coil terminal box (CTB), which is part of the feeders, provides the connections between the magnets on the one hand and the cryoplant, power supplies and data acquisition system on the other.

The instrumentation consists of the sensors attached to the magnet system and associated equipment. Instrumentation signals are transmitted to local panels containing controllers. These local panels are themselves connected to the data acquisition system and interlocks system.

2.1.2 System Boundaries

(1) Boundary to the cryostat
The gravity supports provide the main mechanical support of the tokamak. The gravity supports are connected to the gravity support ring pedestal, which is part of the cryostat. The connection is made by means of interface flanges and stud bolts.

The coil feeders require penetrations at the cryostat wall for magnet feedthroughs.

(2) Boundary to the vacuum vessel
The vacuum vessel is supported by the magnet structure through the vacuum vessel support, which is part of the magnet system. Connection of the vacuum vessel support to the vacuum vessel is made at the support pad, which is part of the vacuum vessel.

(3) Boundary to the power supplies
Current leads installed in the CTBs provide the interface to the power supplies. CTBs are located outside of the cryostat. Connection to the room temperature busbars from the power supply is made at the warm end of the current leads.

(4) Boundary to the cryoplant and distribution system
The CTBs also provide the interface to the cryoplant and distribution system. Helium supply and return lines are connected to the manifolds through a T-section, which is part of the cryoplant and distribution system.

2.2 Specific System-Internal Requirements

2.2.1 Operation

The TF coils, CS, PF coils, CCs and magnet structure shall withstand 100 cooldown and warmup cycles, 1,000 TF charging cycles, and 30,000 equivalent reference burn pulses (including PF system rebias).

All coils shall meet the requirements of the plasma operation scenarios and be compatible with alternative scenarios as specified in DRG1. Each of the PF coils shall also meet the scenario requirements in the ‘back-up mode’ of operation. In this ‘back-up mode’, which is defined in 2.2.7, one of the double pancakes which compose the coil is by-passed.

The 18 coil TF magnet system shall create the stationary toroidal magnetic field specified in DRG1.

The poloidal field system shall operate with either direction of plasma current and either direction of the toroidal field.

The design of the superconducting conductors shall be compatible with AC losses generated by the plasma scenarios and the control actions related to plasma disturbances as specified in Table 1.4-2 of DRG1.

Radiation dose and nuclear heating of the magnet system are defined in sections 1.13 (Table 1.13-2) and 1.15 (Table 1.15-1) of DRG1.

Coils shall not quench during normal operation, including plasma disruptions of up to a certain size. There is one exception to this requirement for the TF coils with a radial plate design where quench may occur during a fast discharge.

The superconducting busbars shall be capable of full current operation (> 1 minute) without causing any damage even if quenched and uncooled.

The current leads shall be capable of full current operation (> 5 minutes) without causing any damage even if uncooled.

Under any normal, upset, emergency, or fault condition, the magnet system shall not cause damage to the confinement barriers that could result in release of radioactivity exceeding the specified limits.

2.2.2 Magnet Charge and Discharge

(1) TF coil normal charge and discharge times

The TF coils current ramp up shall not be faster than 2 hours. A normal discharge shall not last more than 2 hours.

The magnet system shall allow the change in the magnitude of the toroidal field between plasma pulses within the current changing rate compatible with a full charge or discharge in two hours.

(2) TF coil emergency discharge

In the event of malfunctions in other systems (e.g. loss of coolant flow, deterioration of the cryostat vacuum), the TF coils shall be discharged within about 30 minutes to allow a rapid, but controllable, plasma termination, and avoid a fast discharge of the TF coils.

(3) Coil fast discharge

Under certain conditions, such as the detection of a quench in the superconductor, the coils have to be discharged rapidly in resistors (fast discharge). The magnet system shall be designed for 200 fast discharges during its lifetime.

Operation of the magnet system requires a reliable quench detection system, with sufficient redundancy, to trigger a fast discharge of the coils.

The fast discharge time constant (defined in DRG1, section 1.9) shall be determined taking into account not only the magnet design considerations (conductor design, response time of quench detection system, dump voltage, possible overcurrent and voltage due to magnetic coupling between coils), but also the requirements of other tokamak components such as the vacuum vessel (see following note).

Note:
In the case of the TF coils, the minimum time constant of the current decay is 11 s and is limited by the stresses in the vacuum vessel due to induced poloidal currents.
In the case of the CS, PF coils and CCs, the selection of the fast discharge time constants is based on magnet design considerations:
- For the CS, the discharge time constant of the current is selected as 7.5 s;
- For the PF coils, the discharge time constant is selected as 14 s;
- For the CCs, the discharge time constant is set at 20 s.

A 2 s delay shall be assumed between the quench initiation and the start of the current decay (for detection of the quench and operation of the protection breakers) and shall be included in the conductor design.

A fast discharge of a PF coil or the CS shall trigger a simultaneous discharge of the CS and of all PF coils and CCs, but not of the TF coils. A fast discharge of the TF coils shall trigger a simultaneous discharge of the CS and all PF coils and CCs.

The CS shall be ready for recharging 2,000 s after a fast discharge if the coil did not quench.

After a fast discharge of the TF coils, the coils and structures shall be re-cooled and operation shall be able to resume within two days.

If fast discharge of one or several coils was due to a conductor quench, the causes and impact of the quench shall be determined and the impact of resuming operation shall be reviewed before restart of operation.

2.2.3 Vacuum

The maximum allowable helium leak rate shall be consistent with achieving the global leak rate requirements for the cryostat.

The maximum acceptable magnet outgassing rate shall be in accordance with those specified in the ITER vacuum design handbook.

Consideration shall be given to the design of the helium cooling circuits to facilitate leak checks and the localization of leaks.

2.2.4 Mechanical

The magnets must withstand the following;

- Electromagnetic loads acting on the magnets.
- Electromagnetic forces induced on the vacuum vessel and in-vessel components and transmitted to the magnets.
- Self weight and weight of the vacuum vessel and in-vessel components which are supported by the magnets.
- Seismic loads on the magnets and seismic loads transmitted to the magnets from the vacuum vessel and in-vessel components.
- Forces applied during installation and assembly of the magnets.
- Helium coolant pressure loads.

The transmission of primary loads shall not rely on the integrity of organic bonding materials.

The TF coil structures shall provide a load path to support the self-equilibrating electromagnetic forces acting between the TF coils, the CS, the PF coils, CCs and the vacuum vessel (VV) during normal operation, plasma disruption and fault events.

The CS shall be registered vertically and toroidally to the TF coils.

Each PF coil shall be self-supporting for in-plane loads, and shall be vertically supported by the TF coils in a way that provides toroidal registration and relatively free radial expansion and contraction.

The VV supports shall support the VV both vertically and laterally from the TF coils cases. The VV supports shall restrict the toroidal motion of the VV, but allow its radial motion due to temperature changes and operating loads during machine operation, in line with the space allocation.

The VV support shall be designed to withstand the number of disruptions and vertical displacement events (VDEs) specified in the DRG1 annex “Load Specification and Combination”.

The gravity support shall support the weight of the whole machine, and shall resist seismic loads as a seismic class component.

The gravity support shall restrict the toroidal motion of the TF coils, but allow their radial motion during cooldown and warmup. The gravity support shall accommodate the axisymmetric displacements of the TF coils due to operating loads during machine operation.

2.2.5 Cooling system

The cryoplant shall provide simultaneous cooldown to cryogenic temperature of all coils with circulating helium in their cooling passages.

During cooldown, the coolant flow rates in the coils and structures shall be adjusted to limit thermal stresses within acceptable values.

The cooldown of the magnet system shall be performed in parallel with the cryostat and VV thermal shields. The magnet system may be kept colder than the thermal shields (see DGR2, chapter 11). Nevertheless, the cooldown shall be controlled to avoid excessive thermal stresses and interference between the magnets system and the thermal shield.

The cryoplant shall also serve to warm the magnet system from operating temperature to room temperature.

Cooling down to 4.5K or warming up to room temperature for all coils and cold structures shall not take longer than one month.

2.2.6 Electrical

The coil insulation shall be specified to withstand the off-normal voltages produced by a single insulation fault anywhere in the coil electrical circuits, so as to resist the development of cascade shorts.

For the TF coils, the terminal-to-ground voltage shall be limited to 5 kV for fast discharges in normal conditions, and to 12 kV in the event of faults.

For the PF coils, under normal operating and fast discharge conditions, the terminal voltage shall be limited to 15 kV.

For the CS, under normal operating and fast discharge conditions, the terminal voltage shall be limited to 10 kV.

For the CCs, under normal operating and fast discharge conditions, the terminal voltage shall be limited to 3 kV.

Current-carrying parts outside the coils, such as coil terminals and superconducting busbars, shall include redundant barriers to reduce the possibility of a short circuit.

All insulation surfaces, including bus and cooling lines, that are exposed to cryostat vacuum, shall be at ground potential.

Because visual inspection is impossible during operation, and is also very limited outside of operation, regular testing of the coil insulation shall be considered as a means to detect the early stages of insulation degradation. Instrumentation and procedures suitable to monitor insulation quality shall therefore be included in the coil design.

The TF coil turn insulation quality shall be monitored by measuring the insulation resistance between the conductor and the radial plate.

The PF coil conductors shall be provided with ‘double insulation’ to allow the detection of impending shorts.

The large PF coils (numbers 3 and 4) shall be provided with a very robust electrical insulation and internal protection screens between double pancakes to limit damage propagation in the event of a short.

2.2.7 Maintenance

(1) General maintenance requirements

The coil terminals (connections of the coils to their superconducting busbars) shall be located within the cryostat, near each individual coil. Terminals shall be accessible for disconnection and reconnection by means of hands-on operation.

The electrical insulating breaks in the cooling lines for the individual coil sections (e.g. pancakes or layers) shall be located within the cryostat near each individual coil. Insulating breaks shall be accessible for repair or replacement by means of hands-on operation.

The low potential (ground) side of the cooling lines for the individual coil sections and the cooling lines that are integral with structural components shall be manifolded to reduce the number of lines to be cut or reconnected during initial assembly or subsequent disassembly. This reduction in the number of lines shall be compatible with the requirements for helium leak detection as well as for flow control. These helium supply and return lines shall be grouped in conduits.

The connections of the current leads to the room temperature busbars shall be accessible for disconnection and reconnection by means of hands-on operation.

(2) Repair or replacement of TF coils and the CS

Space and access limitations, as well as electromechanical considerations, do not allow the elimination of a short inside a TF coil or the CS by bridging the faulty part of the coil. In the event of an electrical short in the TF coils or the CS, the faulty TF coil or CS module will require replacement and the design shall, therefore, allow such replacement.

For the replacement of any TF coil, provisions shall be made to allow it with minimum cutting of cooling pipes and ports.

The CS design shall allow its replacement without requiring the removal of the TF coils.

(3) Repair or replacement of PF coils and CCs

The PF coils shall be built with partial repair capability for an internal short. Each PF coil shall be composed of a number of independent double-pancakes with accessible joints such that a faulty double-pancake can be by-passed. In each PF coil, redundant current capability shall be provided to allow full current operation with one double-pancake by-passed (backup mode of operation).

Access to PF coils to allow the electrical bypass of a faulty double pancake shall be provided. For this purpose, a radial space of about one meter from the outer surface of a PF coil shall be provided to carry out the bypass operation and the reconnection of the healthy double-pancakes.

If the replacement of a PF coil is nevertheless required then,

- In case of a lower coil (numbers 5 and 6), it shall be lowered to the floor of the cryostat and cut up to allow its removal. A new coil shall be rewound in the cryostat under the machine.
- In the case of an upper coil (numbers 1 and 2), it shall be removed and replaced by a new coil.
- The removal of the two large coils (numbers 3 and 4) would require cutting vacuum vessel ports and water cooling pipes. To avoid such operations, these coils shall be design to provide robust electrical insulation system (see 2.2.6). If replacement of a coil is nevertheless required, the coil shall be removed and replaced by a new coil.

The failure of one CC would result in some reduction in the field correction capability but would not normally require the replacement of that coil. If replacement is found necessary, for example due to multiple CCs failure, the CCs shall be replaceable without removing any of the TF coils.

2.2.8 Manufacturing

For each magnet manufacturing contract, a QA programme shall be established in accordance with the ITER QA manual.

Specific factory and final acceptance tests shall be specified for each component of the ITER magnet system.

2.2.9 Assembly

Clearances between the magnets and adjacent components, in particular the VV thermal shield, shall be sufficient to avoid damage due to interactions under all specified operating conditions.

2.2.10 Testing

The TF coils and CS modules which use Nb_3Sn superconductor shall be cold tested before assembly in the tokamak. The cold test will include, as far as possible, operation at full current and the demonstration of the satisfactory operation of joints.

2.2.11 Instrumentation and Control

During operation, including cooldown and warm-up, real-time monitoring of cooling conditions, such as temperature, pressure and flow of the helium coolant, shall be performed to detect abnormal conditions or anomalous heat loads.

During charging and discharging and during operation, pancake and ground voltages in coils and the ground connections of all structural components shall be monitored to detect developing short circuits.

Displacements of TF coil cases, CS pre-load structure, PF coil clamps, VV supports and gravity supports shall be monitored to detect abnormal structural behavior that could lead to failure.

The quench detection systems shall include the monitoring of resistive voltages in every pancake and also the monitoring of the coolant pressure or mass flow rate.

2.3 Codes and Standards

The magnet system shall be designed in accordance with, but not limited to, the following ITER documents, all of which are attached to DRG1:

- Structural Design Criteria (SDC)
- Electrical and Superconducting Design Criteria
- Material Properties Handbook (MPH)