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Magnetic fusion facilities — Requirements for the safety systems raised by the application of the superconducting technology

Installations de fusion par confinement magnétique - Exigences applicables aux systèmes de sûreté soulevées par l'application de la technologie supraconductrice

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Contents

Page

Foreword ... **iv**

Introduction ... **v**

1 Scope ... **1**

2 Normative references ... **1**

3 Terms and definitions ... **1**

4 Application of superconductivity in fusion facilities ... **4**
4.1 Overview of the superconducting magnet system ... 4
4.1.1 General ... 4
4.1.2 Cryogenic technology needed in superconducting magnet system ... 4
4.1.3 Auxiliary systems to the superconducting magnet system ... 5
4.2 Safety systems present in fusion facilities ... 5
4.2.1 Confinement system ... 5
4.2.2 Nuclear shielding system ... 5
4.2.3 Auxiliary safety system ... 6

5 Requirements for confinement system ... **6**
5.1 General ... 6
5.2 Requirements associated with the presence of superconducting magnets ... 6
5.3 Protection of confinement system against magnetic energy ... 7
5.4 Protection of confinement system against other hazard ... 7

6 Requirements for radiation protection ... **8**
6.1 Safe operation ... 8
6.2 Maintenance and repairability ... 8

7 Requirements specific to other systems ... **10**
7.1 Plasma performance monitoring system ... 10
7.2 Magnetic diagnosis and monitoring system ... 10
7.3 Quench detection and protection system ... 10
7.4 Diagnosis and monitoring system in support of confinement systems ... 11
7.5 Other requirements ... 11

Annex A (informative) **Example of Paschen curve** ... **12**

Annex B (informative) **Examples of radiation design limits for super-conducting coils in ITER and DEMO** ... **13**

Annex C (informative) **Examples of peak factors used in the ITER one dimensional neutronic design analyses** ... **14**

Annex D (informative) **Vacuum vessel, first wall and blanket examples** ... **15**

Annex E (informative) **Arcing prevention in superconducting magnets** ... **17**

Bibliography ... **19**

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Foreword

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Introduction

Fusion energy has the potential to serve as the ultimate carbon-free energy solution. Following significant development and improvement on fusion science and technology, magnetic confined devices such as tokamak or stellarators have become one of the main routes pursuing the fusion energy for a productive realisation. Therefore, magnets are essential components of any Tokamak fusion device. After over decades' development, the magnets applied in Tokamak devices have evolved from ordinary magnets to superconducting magnets. For instance, EAST in China, KSTAR in Korea and JT60-SA in Japan are all superconducting tokamak devices. ITER (international thermonuclear experimental reactor) is the first fusion nuclear reactor in the world with three main sets of superconducting magnets, namely TF (Toroidal Field) magnets, PF (Poloidal Field) magnets and CS (Central Solenoid) magnets. For future magnetic fusion based reactors, such as various fusion DEMO reactors (DEMOnstration reactors) proposed by different stakeholders, same types of magnets will be anticipated in place in order to confine and shape the fusion plasma core, and to drive the plasma current.

There are two primary safety functions in a fusion facility, namely the confinement of radioactive species and the shielding protection against ionizing radiation. A set of safety systems need to be implemented in order to realise the safety functions. For example, the confinement function would be realised by various static and dynamic confinement barriers; the shielding function would be supplied by bulk of components for the attenuation and absorption of neutrons and photons. The introduction and the application of the superconducting technology would bring changes to subsequently lead to new requirements to the safety systems in fusion facilities. There are some new risks and hazards associated with superconducting magnet systems, e.g., the accidental discharge of the magnetic energy which may threaten the integrity of the first confinement barrier, namely vacuum vessel in a fusion facility; the accidental outbreak of the cryogenic coolant helium which may breach the cryostat and/or penetrations through building walls that are also part of confinement barriers. In a D-T fusion facility, the superconducting magnet system would inevitably operate in a radiation environment, thus, the shielding capability of such fusion facility should not only be adequate to protect the workers and the public, but also aim to minimise the possibility to compromise the reliability and the performance of the electronics and devices employed by the superconducting magnet system. It should also facilitate the repairability of large-scale superconducting magnet by reducing and minimising the radiation exposure to an as low as reasonably achieved (ALARA) in the associated nuclear environment. Moreover, it should reduce the amount of radioactive waste by reducing the activation of structural material of coils.

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Magnetic fusion facilities — Requirements for the safety systems raised by the application of the superconducting technology

1 Scope

This document specifies requirements concerning safety systems raised by the application of superconducting magnets in fusion facilities. Safety systems include confinement systems (both static and dynamic types), shielding barriers, penetrations, and supporting systems such as instrumentation and control.

The requirements are applicable to both normal and abnormal operation of a fusion facility. For instance, the radiation protection shall be adequate in order to permit the hands-on operation to the electronics and parts for inspection, maintenance and replacement; the hazards associated with superconducting magnets, such as the loss of superconductivity (quench), Paschen breakdown following helium and voltage leakage, shall be prevented from breaching the integrity of safety systems.

This document will facilitate the design and assessment of the safety systems in a fusion facility with superconducting magnets for all configurations, such as tokamak, stellarator and magneto-inertial fusion devices. Based on the advancement and maturity of the tokamak configuration, this document outlines safety requirements mostly derived from the tokamak configuration but also applicable to other configurations and layouts that may be adopted by future fusion devices.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 16646, *Fusion installations — Criteria for the design and operation of confinement and ventilation systems of tritium fusion facilities and fusion fuel handling facilities*

ISO 17873, *Nuclear facilities — Criteria for the design and operation of ventilation systems for nuclear installations other than nuclear reactors*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org

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3.1
confinement system
containment system
system constituted of a coherent set of physical barriers and/or dynamic systems intended to confine radioactive substances in order to ensure the safety of the workers and the public and the protection of the environment, including the mitigation of the release of radioactive materials

Note 1 to entry: According to IAEA definitions, a containment system concerns the containment structure and the associated systems with the functions of isolation, energy management, and control of radionuclides and combustible gases. This containment system also protects the facility against external events and provides radiation shielding during operational states and accident conditions.

Note 2 to entry: To clarify magnetic confinement is to confine plasma and has no connection to the confinement.

3.2
first wall
FW
first layer of components facing the fusion plasma core including systems and elements of a vacuum vessel located closest to the plasma combustion area and performing confinement function, heat removal function and protection of personnel and equipment against ionizing radiation function

Note 1 to entry: First wall has to endure the high heat flux and neutrons from the plasma to protect components outwards. An example is shown in Figure D.1.

3.3
blanket
one of the main components and structures surrounding the fusion plasma core, located between the first wall and the vacuum vessel

Note 1 to entry: Blanket is the main energy carrier from the heat deposition from fusion neutrons and breeding blanket should also serve as the tritium producer to supply the fuel in future D-T fusion facilities.

3.4
divertor
one of the main structures surrounding the fusion plasma core, situated at the top or bottom of the vacuum vessel

Note 1 to entry: Divertor extracts heat and exhaust produced from the fusion plasma, minimizes plasma contamination, and protects the surrounding components from thermal and neutronic loads.

3.5
vacuum vessel
VV
sealed metal container that provides vacuum environment to house the fusion reactions and may act as a first safety confinement barrier for radioactivity in fusion facilities

Note 1 to entry: Vacuum vessel provides a high-vacuum environment for the plasma, improves radiation shielding and plasma stability.

3.6
port
region dedicated to house auxiliary systems and may be part of the vacuum vessel

Note 1 to entry: Examples of ports include vertical port, equatorial port and divertor port.

Note 2 to entry: The auxiliary systems housed in the ports are notably the heating system to heat up the fusion plasma, vacuum systems to extract the ash and to maintain the quality of plasma, diagnostic systems to measure and to monitor the performance of fusion plasma operation, cooling pipes extended from those components inside the vacuum vessel, power supply cables and divertor exhaust extracting systems.

Note 3 to entry: For Tokamaks, ports may locate at the top of the D-shape vacuum vessel, at the mid-plane, namely equatorial port, and in the region of divertor.

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Note 4 to entry: The ports may be the path for the remote handling operation.

3.7
superconducting magnet
magnet made of superconducting wire, which can carry much higher current and to produce stronger magnetic field than conventional magnets

3.8
winding pack
<superconductor> pack composed of multiple cables mixed with superconductor, conductor, insulation and cryogenic coolant

3.9
thermal shield
TS
metal layer cooled with cryogenic fluid to provide the thermal insulation between the main body of *vacuum vessel* (3.5), the *superconducting magnets* (3.7) and the cryostat aiming to stabilize the performance of *superconducting magnets* (3.7)

3.10
cryostat
sealed steel container to provide high vacuum and ultra-cool environment to allow the performance of *superconducting magnets* (3.7)

3.11
quench
<superconductor> transient process that the temperature of the superconductor rises so as to lose its superconductivity

Note 1 to entry: Transient process where the stored energy in the superconducting coil is released as heat upon loss of superconductivity (i.e. when the critical current, critical field or critical temperature of the superconductor is exceeded).

3.12
feeder system
system consists of a large number of pipelines to deliver electrical power, coolant and control and diagnostic signal wiring into the *superconducting magnet* (3.7) at the same time

Note 1 to entry: Feeder systems are connected with the magnets at the terminal areas and passed through the thermal shield and cryostat, then are connected with the external cryogenic and power supply systems.

Note 2 to entry: Feeder systems are essential for the operation of a superconducting magnet.

3.13
cryogenic system
system used to realize and maintain the low temperature operation of the *superconducting magnet* (3.7)

Note 1 to entry: Cryogenic system is located outside cryostat.

3.14
power supply system
system used for energising and deenergising the *superconducting magnet* (3.7) system

Note 1 to entry: The power supply system includes quench detection and protection mechanisms.

Note 2 to entry: The power supply system is located outside the cryostat.

3.15
control and diagnostic system
<for magnet> system mainly used to control the operation state of the magnet, obtain various operation information of the magnet

Note 1 to entry: They are connected with the magnets and main control system through the signal wires.

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Note 2 to entry: The control and diagnostic system provides supportability for the operation safety of the magnet.

Note 3 to entry: An example of monitoring and control of magnet system is provided in Annex D.

4 Application of superconductivity in fusion facilities

4.1 Overview of the superconducting magnet system

4.1.1 General

Superconducting magnet system are notably used in magnetic confined fusion devices, for example stellarators or Tokamak fusion machines. The next sentences give the example of a Tokamak machine as the safety topics are similar and Tokamak safety issues cover those from a stellarator.

Example of the application of superconducting magnets is in tokamak fusion devices, which are primarily composed of three groups: toroidal field (TF) magnets, poloidal field (PF) magnets and central solenoid (CS) magnets, and an additional group, i.e., the correction coils (CC), to compensate the error field of the tokamak fusion device.

— TF magnets generate a high toroidal magnetic field to confine the plasma in a dedicated region housed in the vacuum vessel.

— PF magnets shape and position the plasma by changing the current of magnets constantly, so as to maintain the plasma equilibrium for Tokamak machines; stellarators have no such a system.

— CS magnets breakdown and heat the plasma by controlling the magnetic flux to maintain the long-term operation of the plasma for Tokamak machines; stellarators have no such a system.

— The CC are used to correct TF and PF system variations and are located outboard of the TF coils and between the PF coils.

The superconducting magnet systems introduce safety risks to be properly addressed in the design or operation of the fusion facility. These risks could create challenges on confinement systems or on radiation shielding materials.

These risks come :

— from the use of cryogenic fluids (e.g. helium, nitrogen, in some cases also hydrogen): this may lead to thermal or pressurising effects in case of leakages, as well as to fire/explosion risks if the cryogenic fluids is combustible,

— from the energy stored in magnets, potentially leading to quenches, arcs or short-cuts, that can themselves lead to leaks, fire or explosion events, together with the damage of confinement or shielding systems.

Therefore, defence in depth principles such as prevention, early detection and mitigation should be implemented to tackle these risks.

4.1.2 Cryogenic technology needed in superconducting magnet system

The cooling capacity of the cryogenic refrigerator shall be able to adequately cool the superconducting magnet system through a low temperature cryogenic distribution system. For example, the typical operating temperature of low-temperature superconducting magnet shall be in the range of 3,8 K to 4,5 K, while the corresponding range for high-temperature superconducting magnets is typically 10 K to 80 K; and the superconducting magnet will be forced-flow cooled by the supercritical helium or hydrogen driven by a large flow refrigerator. Nitrogen can be used to provide 80 K to supply the cooling of auxiliary systems to the superconducting magnets.

To simplify the practical configuration, the main components of the cryogenic system should usually be located near the cryostat to supply the low-temperature and high-pressure cryogenic coolant to the magnet through the cooling pipe penetrating through the cryostat.

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