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Electromagnetic analysis, structural integrity and progress on mechanical design of the ITER ferromagnetic insert

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ABSTRACT

Ferromagnetic material is used to reduce the toroidal field ripple in JFT-2M [H. Kawashima, et al., Demonstration of ripple reduction by ferritic steel board insertion in JFT-2M, Nucl. Fusion, 41 (2001) 257–263] and JT-60U [H. Takenaga, the JT-60 Team, Overview of JT-60U results for development of steady-state advanced Tokamak scenario, Proceedings of the 21st IAEA Fusion Energy Conference, Chengdu, China, 2006]. In ITER, since the ferromagnetic material is inserted in the space between the double walls of ITER Vacuum Vessel (VV), it is called “ferromagnetic inserts”. Suitable material is selected to satisfy the design requirements of ITER. The proper location and amount of the ferromagnetic inserts are optimized with the goal of reduction of the toroidal field ripple. The ferromagnetic inserts are designed to minimize electromagnetic forces acting on them. The electromagnetic forces have been calculated with the latest disruption scenarios. Magnetization forces due to magnetic fields have also been calculated. Structural integrity has been validated by a structural analysis.

1. Introduction

The space between the double walls of the ITER Vacuum Vessel (VV) is filled with stacked steel plates called “in-wall shielding” as shown in Fig. 1. It has two main functions; one is to provide an effective neutron shielding and the other to reduce the toroidal field ripple in the outboard region. The in-wall shielding dedicated to the former function is called the “primary in-wall shielding”. The one used for both nuclear shielding and ripple reduction is called a “ferromagnetic insert”. The primary in-wall shielding and the ferromagnetic insert have basically the same structure but are made of different materials. The ferromagnetic inserts are installed in the plane of each TF coil to minimize the toroidal field ripple. Toroidal ripple reduction will result in a reduction of neutral beam particle and energy loss as well as a reduction of alpha-particle energy loss and heat loss to the first wall.

Since the inter-wall space is used as water passages for cooling of the VV, the in-wall shielding forms cooling channels in the space. The total amount of the in-wall shielding is estimated at 1733 tonnes. Because the VV design has been updated in detail in recent years [3,4], the in-wall shielding design has also been refined keeping its original concept [5].

2. Design description of the ferromagnetic insert

2.1. Material

Both the primary in-wall shielding material and ferromagnetic insert material must satisfy required material properties, such as sufficient mechanical strength, satisfactory corrosion resistance without any surface treatment, acceptable fabrication characteristics, availability and cost. Additionally, high saturated magnetization is required for the ferromagnetic insert material to provide effective ripple reduction. The materials have been selected during the ITER EDA [6,7]. SS 430 ferritic steel was selected to reduce the toroidal field ripple. SS430 has a saturated magnetization of approximately 1.5 T [8]. To obtain suitable magnetic properties, the recommended heat treatment is specified [9]. The heat treatment consists of heating the material to a temperature of 850 ± 25 °C for 2 h, and cooling it at ∼50–100 °C/h to 400 °C. A dry hydrogen or vacuum atmosphere is recommended to prevent oxidation. The specified chemical composition by ASTM A 240/A 240M is shown in Table 1. Additionally, the maximum content of Cobalt and Niobium is limited to less than 0.05 and 0.01 wt.%, respectively, to reduce activation of the material. This is important to limit radiation dose around the primary cooling water system due to corrosion products. Boron-doped austenitic stainless steel is also used to improve neutron shielding performance. The primary in-wall shielding uses only boron-doped stainless steel. The boron-doped stainless steel

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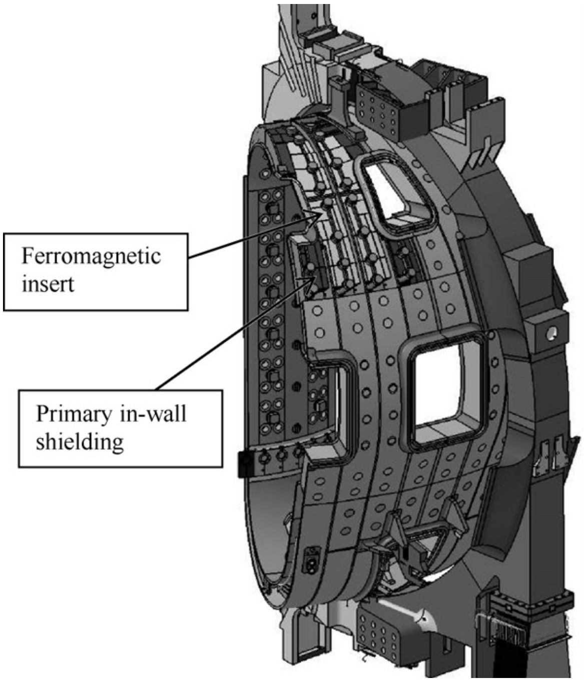

Fig. 1. In-wall shielding (primary in-wall shielding and ferromagnetic insert), a sector of the Vacuum Vessel and a Toroidal field coil.

contains 1–2 wt.% of boron. For the inboard region where efficient shielding performance is required as much as possible, boron-doped stainless steel with 2 wt.% of boron (SS 304B7) is used. For the outboard region where shielding requirements are not so severe compared to the inboard region, boron content is 1 wt.% (SS 304B4). Austenitic stainless steel XM-19 (UNS S20910) is selected as fastener material due to its high strength and corrosion resistance. XM-19 has a similar thermal expansion coefficient to SS316L (N)-IG or SS304 so that thermal stresses due to the difference in the thermal expansion coefficients between shielding blocks and surroundings such as ribs can be minimized. Austenitic stainless steel SS316L(N)-IG is selected to fix the ferromagnetic insert on the VV structure.

2.2. Neutron shielding

Reliable radiation shielding is required for ITER to protect superconducting coils, other cryogenic systems and the cryostat from excessive nuclear heating due to the plasma neutrons and secondary gamma-rays. A suitable combination of steel and water provides efficient shielding performance [10,11]. The calculated optimum steel/water volume fraction is 75/25 which is independent of the boron content as shown in Fig. 2. If the volume fraction of the steel were to be higher than the optimized value (~85% steel), the nuclear energy release in the TFC increases sharply. Therefore the maximum amounts of the steels (both ferromagnetic material and boron-doped stainless steel) are limited so as not to decrease the neutron shielding efficiency. In the actual design, a 60–75% steel fraction including the VV double walls is achieved.

Table 1
Chemical composition of SS430 specified in ASTM A 240/A 240M (in wt.%).

C	0.12 max
Mn	1.00 max
P	0.040 max
S	0.030 max
Si	1.00 max
Cr	16.00–18.00
Ni	0.75 max
Fe	Bal.

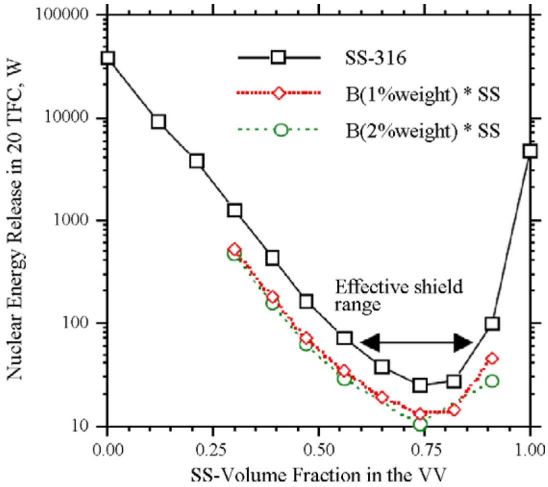

Fig. 2. Nuclear energy release in 20 TFC as a function of steel fraction in 65 cm vacuum vessel [10].

As mentioned above, boron-doped stainless steel is used as shielding material. The toroidal field coil (TFC) heating rate is reduced by a factor of 2–2.4 with the boron-doped stainless steel. The ferromagnetic insert also needs to provide an effective neutron shield. The necessary amount of the ferromagnetic inserts to optimize the toroidal field ripple varies depending on the amount of ripple. The blocks, which have less ferromagnetic material than is required value for shielding, are assembled with boron-doped stainless steel to satisfy the shielding requirement.

2.3. Optimization of the filling factor

In the case of no ferromagnetic inserts, the maximum value of the ripple was ~1% at $R = 8.28$ m (see Fig. 3(a)) and the flux deviation was ~10 mm on the outer part of the separatrix. Since ITER has 18 TF coils, there is in principle the opportunity for 18 ferromagnetic inserts placed symmetrically, whose volumes are all the same so as not to disturb toroidal symmetry of the toroidal field. In the poloidal cross section, they would be in the 12 o'clock to 5 o'clock region in the outboard area where the toroidal field ripple is not negligible [12,13] (see Fig. 4). To optimize the toroidal field ripple, amounts of ferromagnetic material should vary depending on how large the toroidal field ripple is at their locations. Due to apparent practical limitations, previously there were no ferromagnetic inserts planned between the equatorial ports, because the tangential NB ports break toroidal symmetry of the VV as shown in Fig. 5. This causes rather large ripple to remain in this region as shown in Fig. 3(b). Although the ripple can be reduced to a small enough level in most of the region, the maximum value of the ripple and the magnetic field lines deviation were still ~1% and ~10 mm, respectively, at $R = 8.28$ m. This ripple over limited region was considered acceptable for the plasma operation. Nevertheless, heat concentration on the first wall was then a concern Thus to mitigate the ripple also in this region, it has been decided to add ferromagnetic inserts in the equatorial region [14]. As mentioned above, it is impossible to use the same shape of block for the NB sectors as for the regular sectors, but the same volume of ferromagnetic insert can added. Taking into account the space limitation due to the NB port, a filling factor of 0.5 is the possible maximum value in the equatorial region. Calculated amounts of the ferromagnetic inserts are shown in Table 2 in terms of filling factor, defined as the ratio between the volume of the inter wall space and volume of the ferromagnetic