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Measurement of the impacts of the J-TEXT TBM mock-up on the toroidal and vertical magnetic field

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ABSTRACT

A 1/3 scaled mock-up of the China Helium-Cooled Ceramic Breeder Test Blanket Module (CN HCCB-TBM) was integrated into the J-TEXT tokamak to study the eddy current distribution, electromagnetic load and thermal load modes on the TBM during plasma disruption. The J-TEXT TBM mock-up is made of reduced activation ferritic/martensitic (RAFM) steel and supported by a cantilever structure, with the ability to move along the radial direction. To investigate the effects on the equilibrium magnetic field in the presence of the mock-up containing ferromagnetic material, two poloidal arrays of printed circuit board (PCB) coil-type magnetic probes are developed and installed inside the J-TEXT vacuum vessel. The toroidal field (TF) ripple along the toroidal direction and the difference of vertical field (VF) over the plasma region are measured. Corresponding simulations are also performed, and the results fit well with the measured ones. It is shown that the TBM mock-up in J-TEXT will change the shape of equilibrium magnetic field in the vacuum vessel significantly, introduce large TF and VF ripple, especially in low field side in front of the mock-up. On the other hand, the effects will produce only a few potentially troublesome problems on the normal discharge when the recession of the mock-up is up to 15 cm away from the port.

1. Introduction

The requirements of tritium breeding self-sufficiency and high grade heat extracting make the tritium breeding blankets (TBBs) the requisite components in the next-step reactors, DEMO [1,2]. Six Test Blanket Modules (TBMs) and their ancillary systems will be integrated in three dedicated equatorial ports of ITER to demonstrate technologies of DEMO blankets. The China Helium-Cooled Ceramic Breeder (CN HCCB-TBM) is being developed to be tested in ITER as Test Blanket Module (TBM) [3]. According to the size of J-TEXT equatorial port 9 and one third the size of CN HCCB-TBM, a TBM mock-up omitting the cooling channel and modularized submodules was designed and integrated in J-TEXT to study eddy current distribution, electromagnetic and thermal load modes on the TBM structure during plasma disruption in the first phase of the experiments. Through the experiments, the simulation results of transient disruption induced forces and the measurement methods for electromagnetic load could also be studied and verified. Essential data can be acquired for performance verification and optimization design of the TBM. RAFM steel, one ferromagnetic material which is considered as the primary candidate structural material for the blankets in the near future, is used as its structural material.

The J-TEXT tokamak is a medium-sized tokamak with an iron core and circular cross-section plasma. It has a major radius $R = 1.05$ m and a minor radius $r = 0.25$ m–0.29 m with a movable titanium-carbide coated graphite limiter. The main parameters of a typical J-TEXT discharge are centre-line toroidal field $B_t = 2.0$T, plasma current $I_p = 200$ kA lasting for 400 ms [4]. Normally, a tokamak equilibrium magnetic field includes the toroidal field (TF) and poloidal field (PF), which generated by energizing the TF and PF magnet coils to confine, shape and control the plasma. The PF magnet system of the J-TEXT tokamak comprises three groups of coils: vertical field (VF) coils, horizontal field (HF) coils and ohmic heating (OH) coils respectively. Ideally the distributions of TF and VF are axisymmetric. However, because the arrangement of TF coils is spaced, the magnetic field in the inter-coil gap is weaker than that near the coil. The TF ripple produced by the toroidally asymmetric disturbances of TF coils can increase the fast-ion

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losses and have effects on plasma confinement [5–7]. In addition, disturbance of the VF occurs due to the presence of iron core. The distribution of VF strong and weak alternately near and away from the yoke is called VF ripple similarly. Due to the negligible impact of ripple on equilibrium plasma. The VF can still be considered as approximately axisymmetric distribution.

Because of the complex nonlinear magnetic properties of the structural material, the installation of single TBM mock-up will change the magnetic field shape, increase the TF and VF ripple remarkably in the vacuum vessel. The impacts on the distributions of magnetic flux with the mock-up need to be validated by calculations and measurements in advance. Evaluation and mitigation of the perturbation of the magnetic field induced by the TBM in ITER is also a hot topic which deserves research and concern. The simulation results reveal that the ITER TF ripple exceeds 1% in the outboard plasma region near the equatorial plane. Installing ferromagnetic inserts (FIs) in the space between the double walls of the ITER vacuum vessel would reduce the value of the TF ripple as low as 0.4%. The planned TBM will introduces a very large local field perturbation, namely 3 times the uncorrected and 10 times the corrected with the FIs [8,9]. At present, the method of installing the ferromagnetic material to reduce the TF ripple has been verified in JFT-2M [10] and JT-60U [11]. Experiments at DIII-D using a purpose-built three-coil mock-up of TBM have shown that a local TF ripple at one port results in only a small reduction in the plasma performance. The largest effect was a reduction in plasma toroidal rotation velocity [12]. Recent experiments suggest that the n = 1 harmonics (n = number of toroidal periods) plasma response plays a dominant role in determining plasma stability, and n = 1 field compensation would contribute to recover most of the impact on plasma performance of the TBM [13].

However, as important and basic parameter for the operation of the tokamak, measurements of the distributions of the perturbed vacuum magnetic fields with RAFM steel TBM mock-up are still valuable. In the J-TEXT, two magnetic probe arrays are built to measure the spatial distributions of TF and VF along toroidal direction with the mock-up at different positions in detail. The results are compared with the simulated values in this article. By changing the radial install location of the mock-up, the impact degree on the magnetic field changes accordingly to meet the demands of normal discharge and active disruption experiments.

2. Assembly methods of J-TEXT TBM mock-up

The exploded view of the TBM mock-up are reported in [14]. It adopts Chinese low-activation ferritic/martensitic steel (CLF-1 steel, a kind of RAFM steel being developed in China) as structural material [15,16]. For the convenience of deploying sensors and fitting well with the interface support structure, multigroup mounting holes are arranged in the front and back plate of the mock-up. All structure components of the final version are made of about 46.6 kg RAFM steel.

The TBM mock-up was integrated in equatorial test port 9 of J-TEXT, as shown in Fig. 1. The interface assembly method adopts cantilevered support structure. The mock-up could move along the radial direction to meet the position requirements of experiments. A compressible stainless steel corrugated pipe is used to achieve vacuum dynamic sealing. A 316L stainless steel column, which is welded on the back support plate at the other end, is used to support the TBM mock-up. It is hollow inside to reduce the total weight of the support structure and to provide output pathway and EMI shielding for sensor signals. The TBM mock-up is bolted to the support column by a flange with its front surface of the first wall facing plasma directly. A large racetrack flange is connected between the front end of the port cell and the vacuum vessel test port with indium sealing. Six support rods installed at the rear end of the port cell act as supporting and guide mechanisms. The support plate together with the mock-up is mounted on the support rods by six axle sleeves. The support plate and the port cell are also connected by the corrugated pipe. A vacuum environment is formed in a space surrounded by the port cell, the back support plate, the steel corrugated pipe and the J-TEXT vacuum vessel.

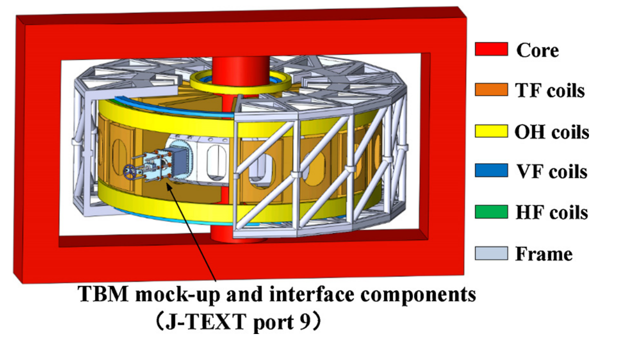

Fig. 1. View of TBM mock-up integration in J-TEXT Port 9.

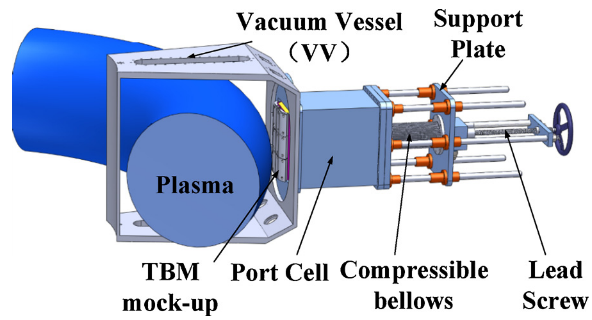

Fig. 2. Supporting and moving mechanism of TBM mock-up.

A lead screw that could be screwed in and out are utilized to move the support plate and the mock-up along the axial direction (the same as the radial direction of the tokamak) of the support rods. The interface supporting and moving mechanism of the mock-up is shown in Fig. 2. Taking into account the simulation results of the mock-up impacts on the equilibrium magnetic field and the experimental requirements comprehensively, the radial movement stroke is designed to 205 mm. The maximum distance inserted into the vacuum vessel of the front surface of the mock-up is 71 mm with the lead screw screwed in and corrugated pipe compressed, touching the plasma edge (r = 0.26 m). On the other hand, the front surface can be recessed from the port by 150 mm (limit position) with the lead screw screwed out and corrugated pipe stretched. Precise positioning is guaranteed by limit bolts in port cell. The results of simulation indicate that moving the mock-up to the limit position can reduce the possible influence on the equilibrium magnetic field remarkably. The increasing rates of the TF/VF ripple will be no more than 30% after the recession of the mock-up, ensuring the operation of the mock-up not to jeopardize performance, reliability and safety of the tokamak.

3. Magnetic field measurement probe arrays

When the TBM mock-up and its supporting and moving mechanism are assembled in the horizontal port, distinct magnetic perturbation with additional TF ripple and VF ripple in toroidal direction is generated due to the nonlinear magnetic properties of RAFM steel. In order to evaluate the impacts on equilibrium magnetic field with the mock-up in different radial positions, compare with the numerical simulation values in the design phase of the assembly structure, and ensure the plasma discharge and disruption experiments carries out well, two arrays of PCB coil-type magnetic probes (Toroidal/Poloidal magnetic probes array) are built to measure the distributions of magnetic field with TF/VF coils operation separately during engineering test phase. The experiments have scanned to measure TF ripple and the difference