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Conceptual design of CFETR divertor remote handling compatible structure

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HIGHLIGHTS

- Conceptual design for the CFETR divertor have been proposed, especially the divertor remote handling compatible structure.
- The degrees of freedom of the divertor are analyzed in order to validate the design the divertor supports structure.
- Besides the ITER-like scheme, a new scheme for the divertor remote handling compatible supports is proposed, that is the rack and pinion mechanism.
- The installation/removel process is verified through simulation in Delmia in order to check design quality for remote handling requirements.

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ABSTRACT

Divertor is one of key components of tokamak fusion reactor. The CFETR is China Fusion Engineering Test Reactor. Its divertor will expose to tritium environment and neutron radiation. Materials of the divertor will be radioactived, and cannot be handled by personnel directly. To develop structure which compatible with robots handle for installation, maintenance and removing is required. This paper introduces a conceptual design of CFETR divertor module which compatible with remote handling end-effectors. The divertor module is confined by inner and outer support. The inner support is only confined divertor module radial, toroidal and vertical moving freedom degrees, but not confined rotating freedom degrees. The outer support is the structure that can confine rotating freedom degrees and should also be compatible with remote handling end-effectors.

1. Introduction

CFETR is a new tokamak device which is now under designing by China national integration design group. Its missions and goals are as follows [1]:

(1) ITER-like; complementary with ITER;
(2) Fusion power: 50–200 MW;
(3) Duty cycle time (or burning time) ~ (30–50%);
(4) Tritium should be self-sufficiency by blanket.

Because of the harsh working conditions, the maintenance for the divertor will have to be handled in remote ways. ITER's Remote handling (RH) scheme divides two sections: radial transportation with Cassette Multi-functional Mover and toroidal transportation with Cassette Toroidal Mover. JT-60SA's RH scheme has a heavy weight manipulator that brings the divertor cassette to the front of the other RH port, which is used for supporting the rail and/or carrying in and out equipments. Then another RH device receives and brings out the cassette by a pallet installed from outside the vacuum vessel (VV) [2]. FAST's RH is similar to ITER, but its outer support system is different from ITER, which is designed as the L shape to lock the divertor to the outer rail [3]. Therefore, how to determine CFETR divertor RH schemes is essential from other divetor RH experiences, especially for the inner and outer support to lock and unlock the divertor in the rail.

2. Establishment of the model

There are 48 divertor modules in the CFETR device, so every module is 7.5° toroidally. The divertor must accommodate with plasma configuration and has the capability to exhaust high heat loads as well as particles pumping and controlling. According to the engineering drawing, the model is designed in the software CATIA,

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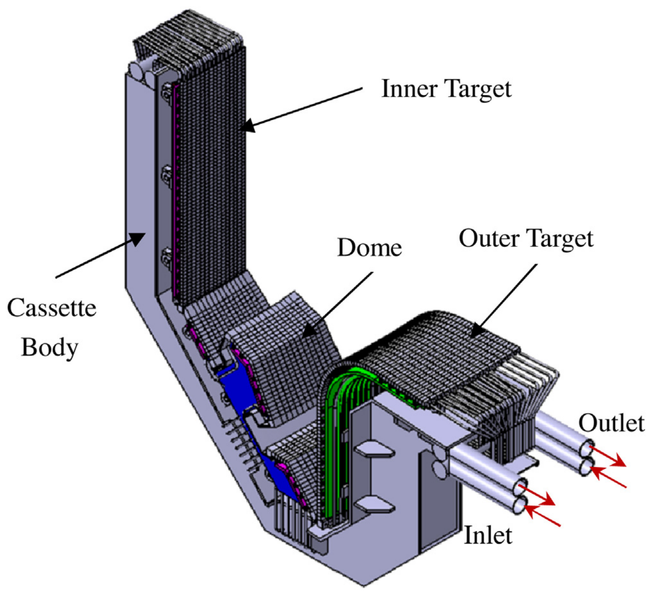

Fig. 1. Concept Design of CFETR Divertor.

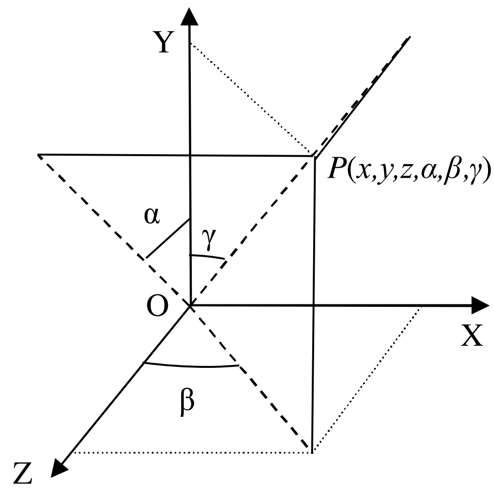

Fig. 2. DOF analysis of a rigid body.

as shown in Fig. 1. Its structure should endure the neutron radiation and must be compatible with remote handling end-effectors. In addition, it must be robust enough to endure the various loads from thermal stress, electromagnetic force and mechanical loads, especially for loads generated by Halo current and eddy current.

3. Remote handling for CFETR divertror

3.1. Background and RH requirements

Because CFETR is a nuclear reactor where D-T operation will be performed, the in-vessel components, plugs and other components would be polluted by tritium activated by high energy neutrons and damaged by higher heat flux and electromagnetic force [4]. Therefore, when RH works in the harsh working environment, its structure should have adequate strength to resist high radiation and the high structure strength material should be considered [5].

3.2. Design of the support structure

When Tokamak works, the divertor will be influenced by electromagnetic force, ELM, VDE, heat flux and current which makes it possible for the divertor to move radially and toroidally. Therefore, support structures in inner and outer sides should be designed to strengthen the divertor positioning. In addition, considering the requirements of RH, the outer interface should be compatible with RH manipulators and it can generate preloading force with a simple mechanism to remove any clearances and avoid "shaking" due to the sudden change of magnetic field.

3.2.1. Analysis of degree of freedom (DOF)

Considering a rigid body has translational motion and rotational motion, its independent coordinate system is determined by the center-of-mass coordinate, as shown in Fig. 2. P is the centroid point of the rigid body, whose values of coordinate can be denoted as (x, y, z, α, β, γ). Here, x, y and z describe the translational motion along the axis; α, β and γ describe the rotational motion around the axis. Therefore, there are six DOFs for a rigid body: $\vec{x}$, $\vec{y}$, $\vec{z}$, $\hat{x}$, $\hat{y}$ and $\hat{z}$.

In order to position the object completely, all six DOFs shall be constraint. As for the divertor, it should be completely constraint in the vacuum vessel with inner and outer supports, as shown in

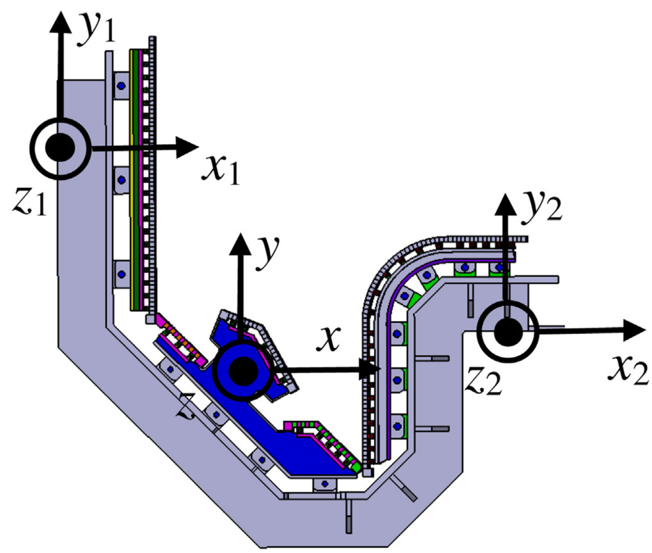

Fig. 3. DOFs of divertor.

Fig. 3. Here, coordinate *xyz* is defined as the global coordinate for the divertor, and inner and outer supports are defined as the coordinate $x_1y_1z_1$ and $x_2y_2z_2$ respectively as the local coordinates.

3.2.2. Requirements for inner and outer supports [6]

(1) Lock/Unlock cassette in place;
(2) Withstand high forces in any direction;
(3) Compatible with remote handling;
(4) (Preload cassette in order to remove clearances.

3.2.3. Design of the inner support

The inner support can position the divertor roughly and it can act as a spring to hold the cassette in place between the inner and outer toroidal rails during plasma operations. At the inboard rail, a socket-type engagement maintains the attachment between the cassette body and the inner hard cover plate attached to the vacuum vessel [7]. It could be ITER-like nose-hook mechanism or hemispherical mechanism [8], as shown in Fig. 4.

Due to the inner support is only confined divertor module radial, toroidal and vertical moving freedom degrees, when the divertor is in the inner rail, following DOFs are constraint: $\vec{x}$, $\vec{y}$ and $\vec{z}$, so the

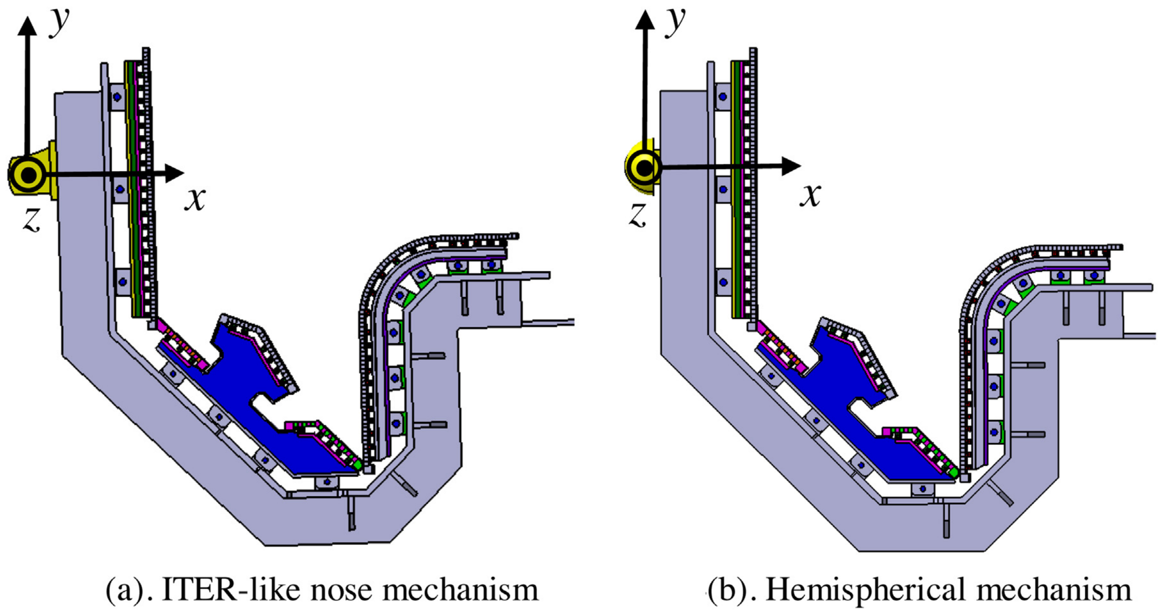

Fig. 4. Inner support.

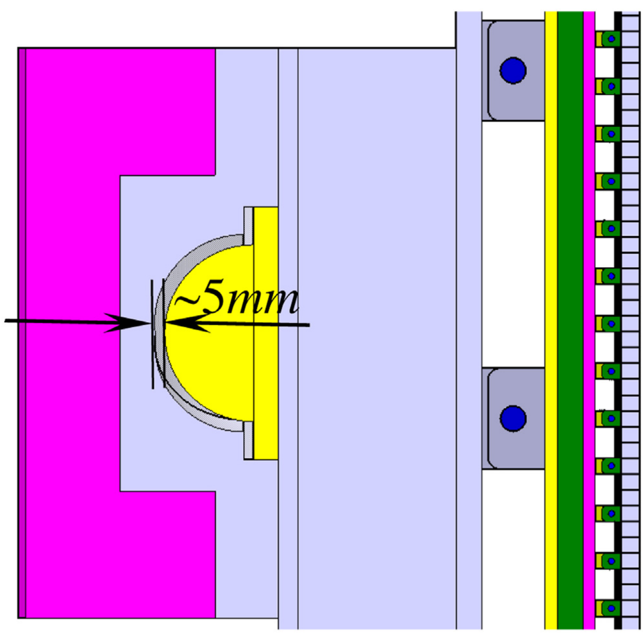

Fig. 5. Preloading clearance.

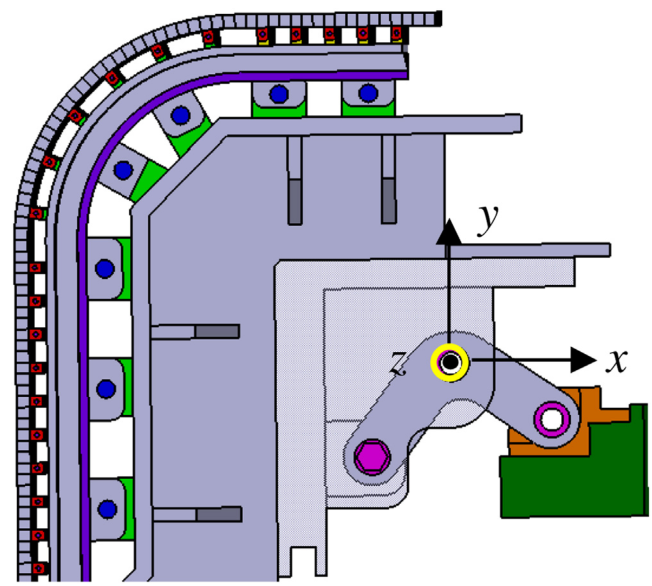

Fig. 6. Knuckle in the outer rail.

other DOFs: $\hat{x}$, $\hat{y}$ and $\hat{z}$ must be constraint together with the outer support.

3.2.4. Design of the outer support

(1) Concept Design I

In this concept design, the outer support is equipped with a big knuckle in order to a robust design according to Ref. [8]. When the inner support is on the rail, the gap distance between the inner support and the inner cover plate is ~5 mm, as shown in Fig. 5. Then the knuckle will rotate into the outer socket which is bolted to the vacuum vessel outer toroidal rail, as shown in Fig. 6.

The knuckle is designed as the U shape so as to position the divertor completely, especially to constraint $\vec{z}$, as shown in Fig. 7. After the pins are inserted into the socket, the cassette can be positioned completely which leads to the divertor be more stable. When the knuckle is in the position, it will constraint the divertor with the inner rail, as shown in Fig. 8. At this phase, the divertor will move ~5 mm radially into inner rail in order to preload the cassette.

(2) Concept Design II

In this concept design, the outer support is equipped with the rack and pinion (R&P) mechanism. When the divertor is fixed in the inner rail, R&P will move to the outer rail. Then R&P will insert its protrude into outer rail from the zero position (coordinate $x_1y_1z_1$) to the support position (coordinate $x_2y_2z_2$), as shown in Fig. 9. In order to limit $\vec{z}$, R&P slot inserted to outer rail is designed to be a rectangle shape, as shown in Fig. 10. From Fig. 10(a), the distance between the slot edge and the outline is L, so it can constraint $\vec{z}$. At the same time, the slot will be inserted into outer rail protrude to support the divertor, as shown in Fig. 10(b). The final solution for the divertor located in the rails is shown in Fig. 11. Then R&P mechanism also preloads the cassette.

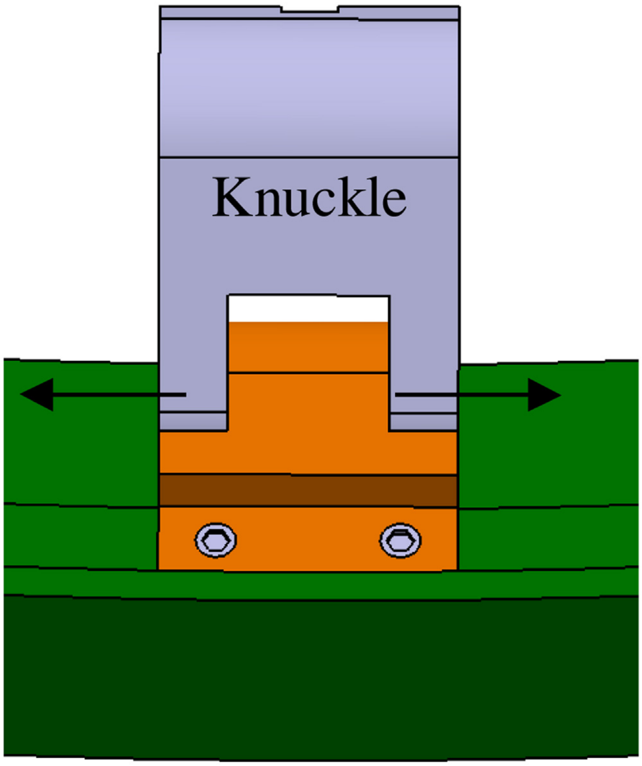

Fig. 7. U shape of the knuckle.

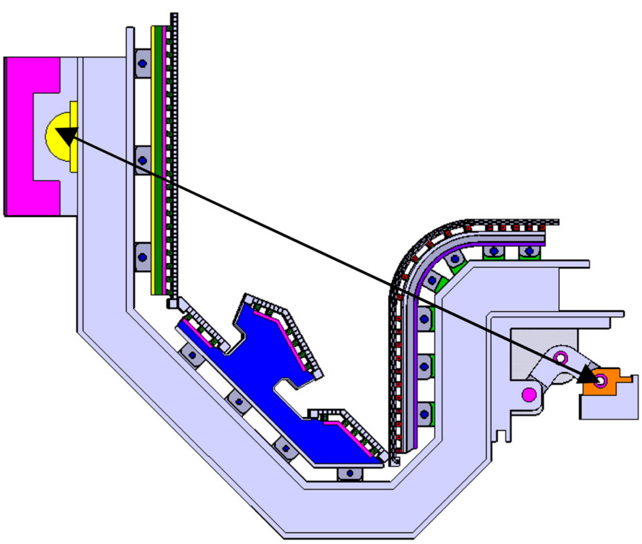

Fig. 8. Cassette preloading I.

4. Simulation in Delmia

There are 16 ports in CFETR, so 3 divertors located in front of the ports named the central divertor and located either to the left or right-hand side of the central divertor named the second divertor are handled via each port. Compared to the central divertor, the second divertor needs to be rotated around device central axis to fix them on the rail.

The central divertor installation process in Delmia can be described as follows:

(1) The divertor is grasped by the manipulator and then moves into vacuum vessel radially;

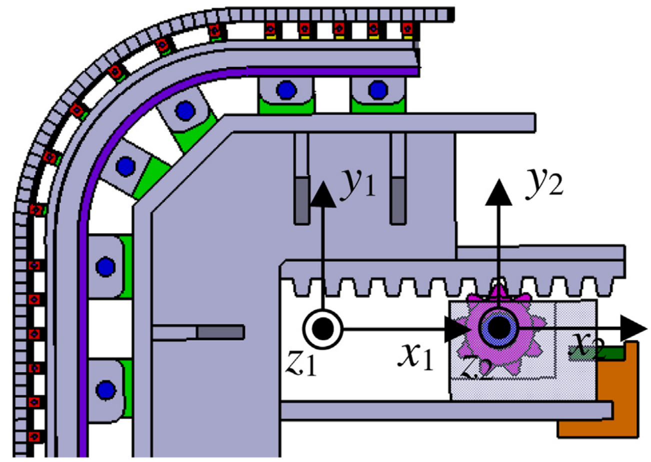

Fig. 9. R&P in outer rail.

(2) The inner support moves into the inner rail, and the gap between the inner support and inner cover plate is ∼5 mm to preload;
(3) The outer support moves into outer rail: (Concept I) the knuckle rotates to the rail, then pins combine the knuckle with the outer rail; (Concept II) R&P mechanism moves to the rail, then it will be locked with cassette by a pin.

The second divertor installation process in Delmia can be described as follows:

(1) The divertor is grasped by end-effectors and then moves radially into vacuum vessel;
(2) The inner support moves into the inner rail, and it is on the edge of VV inner rail in order to toroidal moving;
(3) The outer support moves into the outer rail: (Concept I) the knuckle rotates to the rail, then pins combines knuckle with outer rail; (Concept II) the R&P mechanism moves to the outer rail, and then it will be locked with cassette by a pin;
(4) The inner support moves into the inner rail.

The simulation process can be described by PERT chart. It describes how the simulation operates. The PERT chart of central and second divertor installation in Delmia can be described as follows.

4.1. Simulation results

The objectives of simulations are:

(1) To simulate the cassette locking/unlocking process in the virtual environment;
(2) To simulate the divertor installation process;
(3) To check whether there is any interference between the divertor and other components.

Through simulation, all objectives can be realized. Both concept design I & II can be installed/removed to/from rails, especially the outer supporting working procedures can be vividly seen from simulation. Besides, the interfaces between divertor and other in-vessel components can be detected, then the supports could be optimized in the virtue environment rather than on-site.

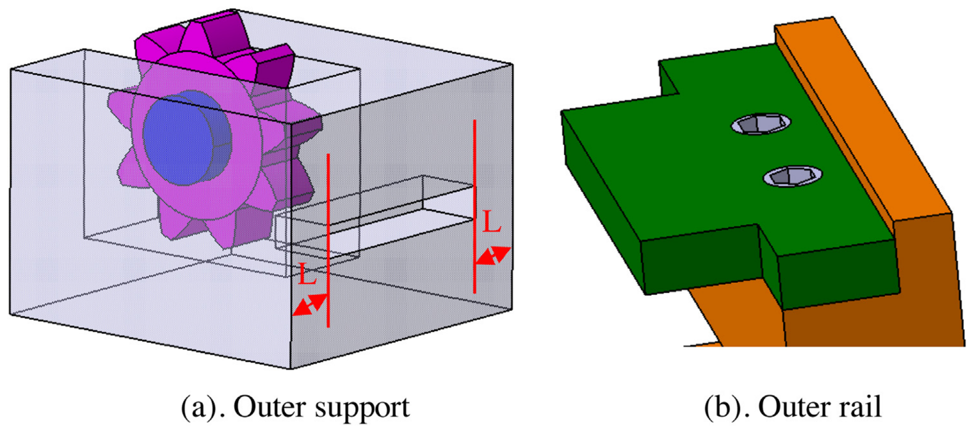

Fig. 10. Outer support and rail.

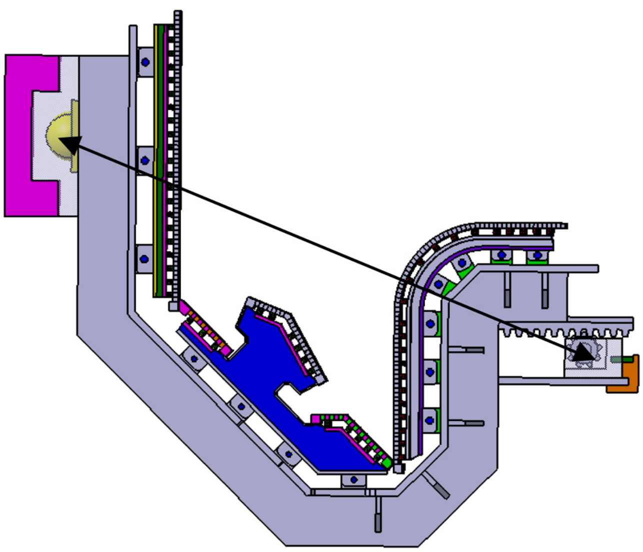

Fig. 11. Cassette preloading II.

5. Conclusion

This paper focuses on the conceptual design of CFETR divertor and its inner and outer supports considering the requirements of RH. According to the analysis of DOFs of the divertor, inner and outer support schemes are put forward. In order to validate the design, simulations were operated in Delmia, where it is possible to have a simultaneous vision of these two schemes. The simulation results show that all schemes can be available for the divertor. However, due to the Concept Design I is learned from ITER solution schemes, and the knuckle needs very accurate geometrical and dimentional tolerances, and it might cause unwanted vibrations during Tokamak operation periods [9], so the Concept Design II might be adopted as the support for the CFETR divertor. In addition, the R&P mechanism can also compensate errors which may be generated by installation process. What's more, whether they can bear the weight, we will validate them in the next step, and to do some optimizations.

References

[1] Jinxing Zheng, Xufeng Liu, Yuntao Song, et al., Concept design of CFETR superconducting magnet system based on different maintenance ports, Fusion Eng. Des. 88 (2013) 2960–2966.
[2] Takao Hayashi, et al., Conceptual design of divertor cassettte handling by remote handling system of JT-60SA, J. Power Energy Syst. 2 (2) (2008).
[3] G. Di Gironimo, et al., Innovative design for FAST divertor compatible with remote handling, electromagnetic and mechanical analyses, Fusion Eng. Des. (2015), http://dx.doi.org/10.1016/j.fusengdes.2015.03.016.
[4] Zibo Zhou, Damao Yao, Pengfei Zi, The research activities on remote handling system for CFETR, J. Fusion Energy (2014), http://dx.doi.org/10.1007/s10894-014-9792-4.
[5] Yuntao Song, et al., Concept design on RH maintenance of CFETR tokamak reactor, Fusion Eng. Des. 89 (2014) 2331–2335.
[6] G. Di Gironimo, et al., Concept design of the DEMO divertor cassette-to-vacuum vessel locking system adopting a systems engineering approach, Fusion Eng. Des. 94 (2015) 72–81.
[7] Design Description Document DIVERTOR REMOTE HANDLING SYSTEM PBS—23.02.
[8] V. Komarov, et al., Design progress of the ITER divertor cassette-to-vacuum vessel locking system, Fusion Eng. Des. 82 (2007) 1866–1870.
[9] G. Di Gironimo, et al., Improving concept design of divertor support system for FAST tokamak using TRIZ theory and AHP approach, Fusion Eng. Des. 88 (2013) 3014–3020.