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Physical Study on Robustness of ITER Machine against Disruptions

ITER装置のディスラプションに対する健全性の物理的検討

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Investigation of robustness against vertical displacement events (VDEs) and disruptions is an important issue in designing ITER machine. In recent years, analysis of halo current and vertical force on the vacuum vessel generated by VDE and disruption has been carried out using the DINA code. In this paper, derivation of the maximum halo current and vertical force is described in view of physical constraints on the current quench duration. The electrostatic sheath formed in front of the wall that bounds the plasma gives rise to such a constraint on halo current generation. Updating the halo current model in DINA to include sheath effects, analysis was done consistently with power balance during current quench. Some important issues related to VDE, intervention of vertical stabilization system in VDE, over-current of in-vessel VS coils and position control of runaway electron beam, are also discussed.

1. ITER disruption study

The VDEs and subsequent plasma disruptions release severe electromagnetic load on the vacuum vessel of tokamak devices. To assure robustness of the vessel and in-vessel components against the load, a lot of simulations have been carried out for ITER using the DINA code [1,2].

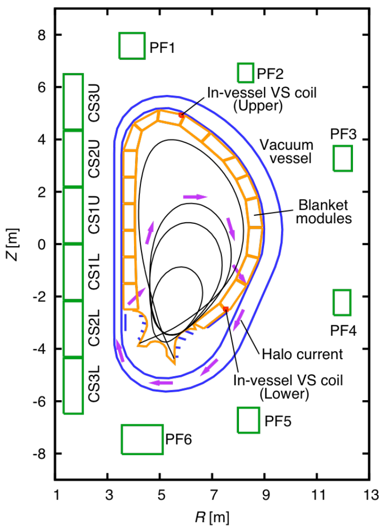

Fig. 1. Structure model of ITER. Sequence of plasma cross-sectional change during VDE is also shown.

The structure model of ITER in DINA consists of poloidal field (PF) coils, vacuum vessel (VV), blanket modules and in-vessel vertical stabilization (VS) coils (Fig. 1). Halo current generation is solved consistently with Grad-Shafranov equation. The largest halo current and hence the largest vertical force occurs in a downward VDE case accompanied by slow current quench (CQ). In the past simulations, electron temperature during CQ, T_e=55eV, was somewhat artificially chosen to produce the CQ time extrapolated from existing experiments. In this study, physical constraints on T_e (thus CQ time) were employed to derive possible maximum of halo current and vertical force.

2. Extension of halo current model

The current quench is a dissipation process of plasma magnetic energy (plasma current) through joule loss. The joule loss to the plasma is eventually emanated through impurity radiation and sheath transmission heat. Hence it follows that T_e, which determines the radiation and sheath transmission cannot be arbitrarily high. The highest T_e occurs when the impurity radiation is negligibly small. The plasma resistivity determined by this highest T_e gives rise to the minimum (slowest) rate of CQ.

The electrostatic sheath modifies the CQ behavior through sheath potential generation in front of the wall. First, the halo current that flows in the wall is regulated under ion saturation current by the sheath potential. Accordingly, plasma resistance becomes higher and the CQ time will be short. Second, the joule input to the halo plasma is also regulated because of the halo current regulation. The maximum T_e determined by power balance between the joule input and the sheath transmission is about 30 eV in the case of ITER.

Results of simulations with and without sheath model are compared in Fig. 2. The CQ time becomes short because the halo resistance increases effectively due to the sheath potential generation. On the other hand, the same level of halo current is generated even if the sheath model is included. The quickened CQ induces destabilizing eddy current in the vessel, so that the plasma moves downward further to generate halo current required to stabilize the plasma itself (bottom plot in Fig.2.)

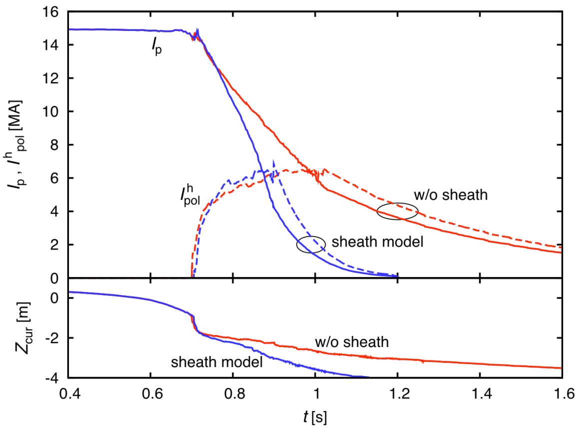

Fig. 2. Effect of sheath on CQ behavior.

3. Influence of VS control

Vertical stability (VS) control during VDE has a potential influence on the vertical force on the VV. If a radial magnetic field is mistakenly applied to the direction of enhancing the vertical displacement further, a larger force will appear in the vessel. Actually this is the case of maximum force in present experiments.

To assess this force, a model of the VS control circuit composed of external PF coils was implemented in DINA. In the case of ITER, because the time constant of the PF coils will be much longer than VDE event duration, it is likely that possible increase will be rather small. The result of simulation confirmed that the force was increased by up to 10% but still within the design margin even if the worst case was considered.

4. Induced VS coil current by VDE

In-vessel VS coils will be introduced in the ITER VV to improve control margin of the VS system (Fig. 1). VDE and subsequent CQ induce huge eddy current in the in-vessel components including the VS coils. To avoid excessive over current in these coils, the upper and the lower VS coils are connected in anti-series such that the inductions of the two coils offset each other. A model of in-vessel VS circuit was newly installed in the DINA code and the coil current was documented for supporting the design.

5. Runaway electron control

Generation of runaway electron (RE) is another concern in the robustness of the VV. Large plasma of ITER size is prone to generate RE. Without appropriate measures, REs would hit the wall eventually resulting in a significant damage. Primary candidate of RE suppression is the repetitive injection of gas. However it is still desirable to spare alternative schemes for backup. Vertical position control of RE beam will be a key point if it could keep the beam from touching the wall until the beam energy is sufficiently dumped due to collisions with neutral gas.

Control boundary of RE beam was explored using the in-vessel VS circuit model of DINA. It was revealed that vertical position control of RE beam would require a high runaway current (~12MA) together with some extension of the present design limit of VS coil current.

6. Summary

Halo current model was extended to include effects of sheath. Simulation result shows that the CQ time should be shorter by 1/2 than the present specification of ITER VDE scenario to satisfy the power balance during CQ. However, the same level of halo current is generated, indicating that the halo current must be consistent with the requirement for stabilizing the vertical movement of the plasma. The vertical force on the VV will be reduced somewhat owing to the shorter CQ time. Robustness of the VV was confirmed even if the (wrong) intervention of VS system was considered. Possibility of the RE beam control still remains unresolved. It should be noted that the model uncertainty is large in RE generation and detailed model development is necessary for further study.

References

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[2] M. Sugihara *et al*: Nucl. Fusion **47** (2007) 337.
