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High-beta spherical tokamak start-up by using outer PF coils and plasma merging in UTST

UTST装置における外部PFコイルとプラズマ合体を用いた高ベータ球状トカマクの立ち上げ

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Center-solenoid-free start-up of spherical tokamak plasma was demonstrated by using outer poloidal field (PF) coils and merging technique in UTST device. Three pairs of PF coils are employed to form null points inside the vacuum vessel and initial plasma current of 80 kA was achieved. During plasma merging, it was found that 30~40 % of the poloidal magnetic energy was converted to the plasma thermal energy. More efficient formation and merging heating are required to establish high-β ST with enough density and magnetic flux for neutral beam injection heating and current drive.

1. Introduction

Spherical tokamak (ST) [1] is an attractive candidate of fusion core with attracting features of high-β, good stability, and good confinement. Its small aspect ratio, on the other hand, severely reduces available volume at the inboard side of the ST device. Since superconducting toroidal field (TF) coil and realistic neutron shield in the ST reactor will consume most of the central region, downsizing or total removal of center-solenoid (CS) coil is crucial for ST reactor development. Various CS-free start-up methods [2] are investigated using waves (EC / EB / LH / Alfvén), helicity injection (coaxial / local), and outer PF coils [3] + merging [4].

UTST device [5] was developed in order to investigate highly-efficient start-up scheme of high-β STs by using plasma merging technique, in which magnetic reconnection of the poloidal magnetic fields of two torus plasmas provides high-power ion heating to form high-β equilibrium in a very short period (< 0.1 ms). In this paper, experimental results from the initial ST start-up using outer PF coils are presented and possibility on the high-β ST formation by merging method will be discussed.

2. UTST Plasma Merging Device

The UTST device (fig. 1) consists of a cylindrical vacuum vessel, a TF coil, a CS coil, a pair of EF coils, and four pairs of PF coils. Although a conventional CS coil is equipped on the UTST device, outer PF coils are utilized to initiate torus discharge with formation of two null points on the upper and lower sections of the device. The vacuum vessel was built in such a way that the electric field induced by the outer PF coils can sufficiently penetrate.

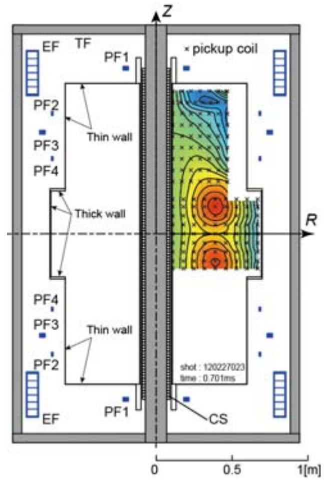

Fig.1. Cross-sectional view of UTST device

3. ST Formation by Outer PF Coils

In UTST, combination of three outer PF coils produces null points inside the vacuum vessel to achieve long connection length condition for torus breakdown. Fig. 2 shows the evolutions of poloidal magnetic flux surfaces in the upper section of UTST device during the ST formation period of (a) vacuum and (b) plasma formation cases. Though large magnetic flux of up to 40 mWb is provided by the outer PF coils, breakdown does not take place till very end of the coil-current ramp-down phase, because the null point is not formed in the early timing. The red lines in fig. 2 (a) indicate the results from eddy current calculation and show good agreement with experimental results. It was found that rapid buildup of the plasma current began at the timing of null point appearance at about t ~ 0.6 ms. Fig. 2 (c) shows the magnetic flux evolution due to the plasma current (and eddy current induced by plasma current). The plasma current was initiated near the null point location and amplified by the change of magnetic flux stored inside the null point. Thus the applied poloidal flux was not efficiently utilized to drive plasma current in the present condition. About 10 mWb out of 40 mWb was trapped in the closed flux surface of ST. Fig. 3 shows the achieved plasma current of initial STs as a function of total current flowing in the outer PF coils. The current drive efficiency of the initial ST formation is limited less than 15 % .

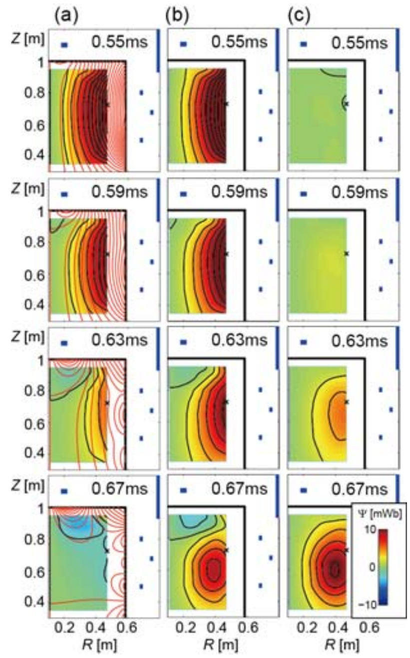

Fig.2. Evolutions of magnetic flux surfaces in the upper section during formation period of (a) vacuum, (b) plasma cases. (c) shows difference between (a) and (b).

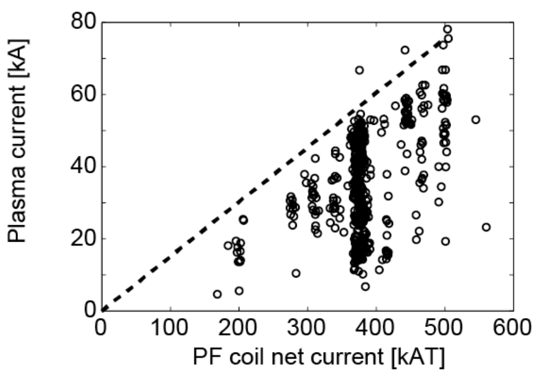

Fig.3. Achieved initial plasma current as a function of total outer PF coil current.

4. ST Merging Formation

Two formed STs in both upper and lower sections are then axially pushed by magnetic pressure and approach each other to merge through magnetic reconnection on the midplane. Here, the poloidal fields of the two initial STs form an anti-parallel configuration and then reconnect. Merging of two ST plasmas also involves high toroidal magnetic field generated by TF coil current, which works as a “guide field” parallel to the reconnection electric field. About 30~40 % of initially stored poloidal magnetic energy was quickly released during fast reconnection phase. Electron and ion temperatures measured after merging phase reflected reconnection heating in which 80 % of the released energy was converted to ion’s thermal energy and 20 % to electron’s.

5. Summary

CS-coil-free start-up of high-β ST was demonstrated in UTST device by using outer PF coils and merging technique. Breakdown and current buildup at upper and lower null points were successfully achieved, however, the flux and current efficiency was not high enough to form initial STs with large poloidal magnetic energy, which should be converted to plasma thermal energy through magnetic reconnection. Optimization of formation scheme and merging heating is required to produce high-β ST suitable for the target plasma of NBI heating / current drive.

Acknowledgments

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