Commissioning of a Non-circular VDE-Free Tokamak with Saddle Coils

T. Kobayashi, S. Hatakeyama, M. Watanabe, H. Tsutsui, S. Tsuji-Iio

Tokyo Institute of Technology, Tokyo 152-8550, Japan

Introduction

In tokamaks, elongated plasmas for high beta and good confinement operation suffer from vertical instabilities. Failure of feedback control of plasma position due to abrupt changes in plasma pressure due to disruptions leads to so-called vertical displacement events (VDEs). The interaction between plasma and first wall due to VDEs can cause the damages of in-vessel components such as blankets by high heat flux and induced electromagnetic forces [1]. On the other hand, it has been shown that the plasma position is robustly stable in a current-carrying stellarator than that in equivalently elongated tokamak plasmas [2]. The aim of our study is to stabilize vertical instabilities of elongated tokamak plasmas by the use of saddle coils as shown in Fig. 1 which generate helically perturbed fields. Although several studies have been made on the effects, they have been conducted in tokamaks with circular cross-sections [3, 4]. For the next step of this study, we constructed a small tokamak device ($R = 0.33$ m, $a = 0.09$ m, $\kappa = 1.8$, $B_t = 0.3$ T) as illustrated in Fig. 2 which has an elongated cross-section to demonstrate the stabilization of VDEs.

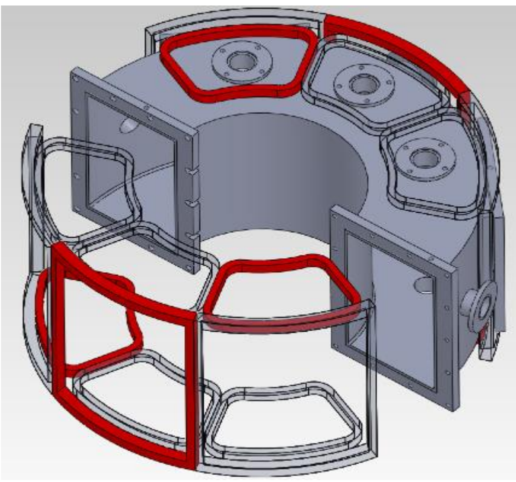

Fig. 1 Example of saddle coils

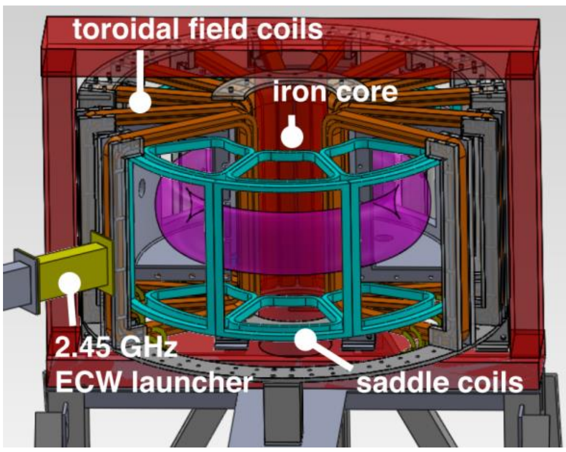

Fig. 2 Illustration of small tokamak device

Effect of saddle coils on VDE

VDEs occur due to bad curvature of vertical field required to make the plasma elongated. The horizontal magnetic field cannot be changed independently from vertical magnetic field with axially symmetric PF coils alone. In order to stabilize the elongated plasma, it is necessary that the horizontal component of magnetic field (B_r) shown in Fig. 3 should be reversed. It is because that the Lorentz force expressed as $I_p \times B$ pulls the elongated plasma vertically when the balance of the force is destroyed with slight vertical plasma shifts. Then if the horizontal magnetic field is reversed near the vacuum vessel, VDEs can be avoidable. Fig. 4 shows the projection of magnetic force lines made by saddle coils on a poloidal cross-section. This indicates that saddle coils can generate horizontal field component which provides a restoring force in combination of the toroidal field.

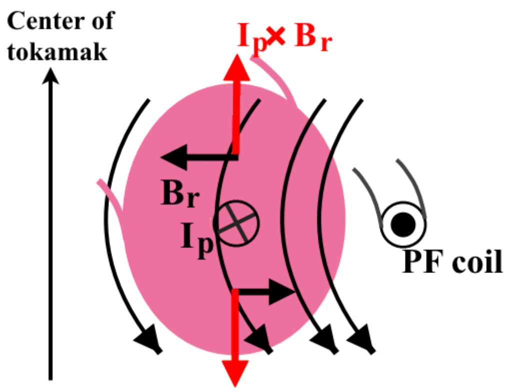

Fig. 3 Poloidal magnetic fields which elongate the plasma

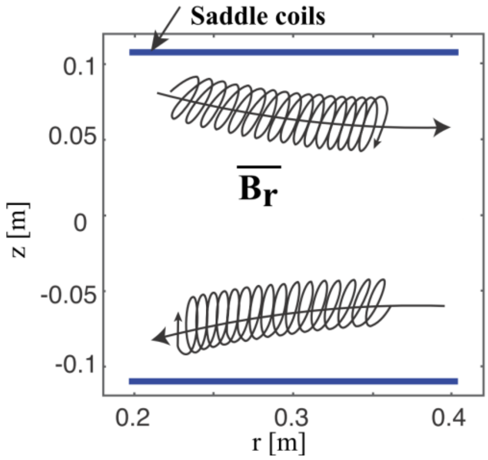

Fig. 4 Projection of magnetic force lines

Commissioning of tokamak plasma

Our new small tokamak device, shown in Fig. 5, has the coil system comprised of 16 toroidal field (TF) and 2 sets of poloidal field (PF) coils, an ohmic heating (OH) coil with iron core. OH coil was wrapped around 20 turns and driven with capacitors using gate drive as a switch. The TF coils are excited with an inverter-driven induction flywheel generator which is

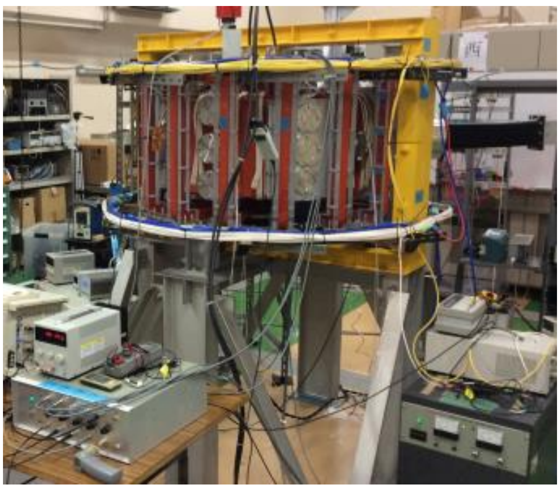

Fig. 5 Photo of small tokamak device under commissioning

controlled to maintain 2.45-GHz electron cyclotron resonance (ECR) at the center of vacuum vessel.

The vertical field generated by the PF coils was constant during discharges by using a DC power supply. PF coils were mounted outside of iron core because this configuration needs no decoupling coil with iron core and is easy for hand-winding. Magnetic sensors were flux loops and a Rogowski coil. Pick up coils will be installed in the shadow of limiters in the poloidal direction. Rogowski coil was wound by hand and achieved current position independence of within 1% error. The signals of flux loops and Rogowski coil were integrated with RC integration circuits in order to measure the plasma current and poloidal magnetic fluxes.

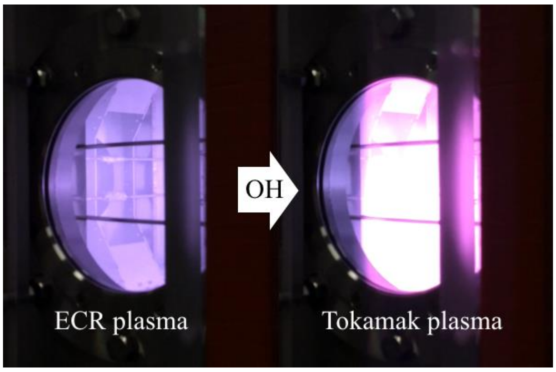

Fig. 6 Tangential images of plasmas under commissioning

In this experimental environment, commissioning was conducted. The plasma current was driven by the OH coil in an ECR discharge with 2.45 GHz microwave as shown in Fig. 6. Figure 7 shows the waveforms of flywheel generator employed to excite TF coils which provide resonant magnetic field. By optimization of the vector control, we succeeded in keeping the generator voltage nearly constant. Accordingly the waveform of the coil current was similar to a square in about 1.5 seconds even when the rotator speed dropped to a half.

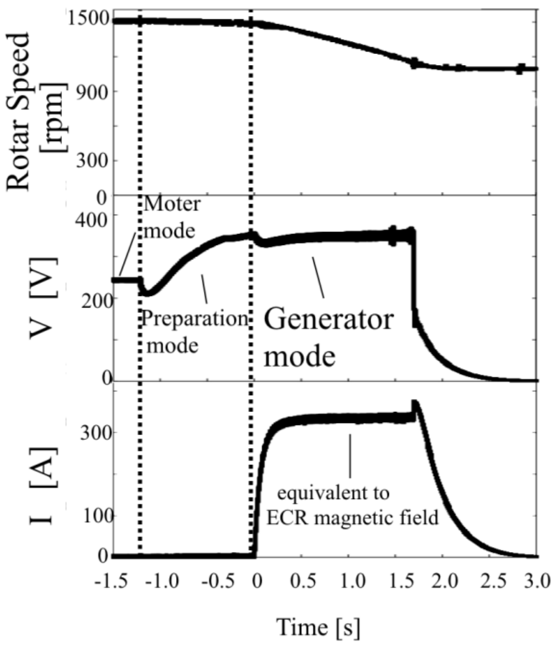

Fig. 7 Waveforms of induction flywheel generator for ECR discharge

Figure 8 shows a result of a scan of the vertical magnetic field (Iv = 0 - 2000 A·turns). The maximum value of plasma current was 3.5 kA. With increasing vertical field coil current, the peak of the plasma current was raised except the case of Iv = 2000 A·turns. This can be inferred that too strong vertical magnetic field pushes the plasma inwardly and the enlargement of plasma cross-section was hindered. Additionally, while the plasma current flowed, the one-turn voltage was almost constant but oscillated due to some MHD instabilities. The safety factor when Ip = 3.5 kA is calculated to be about 3.6 by cylindrical approximation. The waveforms of the OH coil current show that the flux swing of the iron core is not fully exploited.

Summary and future work

We proposed saddle coils for the position control of elongated plasma and now commissioning a new small tokamak device. We obtained the first tokamak plasma with plasma current of up to 3.5kA driven by the OH coil current and with 2.45 GHz microwave for ECR pre-ionization.

Next steps are as follows; firstly, establish tokamak discharges are with toroidal magnetic field up to 0.3 T using a capacitor bank and without ECR pre-ionization. Secondly, elongate the plasma by the feedback control and trigger vertical instabilities by switching off the control. Then the saddle coils will be optimized using a 3-D equilibrium analysis code in order to avoid the VDEs and demonstrate the efficacy of saddle coils.

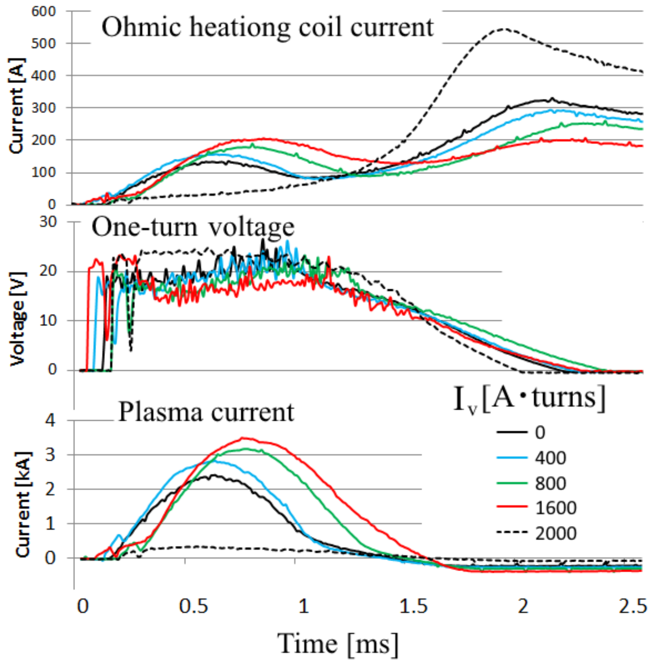

Fig. 8 Variations of I_p time evolution with different vertical magnetic fields

References

[1] T. C. Hender, J. C. Wesley, J. Bialek *et al*., Nucl. Fusion. 47, S128 (2007).
[2] G. Y. Fu, L. P. Ku, W. A. Cooper, S. H. Hirshman, D. A. Monticello *et al.*, Phys. Plasmas 7, 1809 (2000).
[3] H. Ikezi, K. F. Schwarzenegger, Phys. Fluids 22, 2009 (1979).
[4] S. Hatakeyama, Y. Shibata, S. Kawakami *et al*., Proc. EPS2012, P1.046 (2012).