PLASMA PRODUCTION IN A TOKAMAK WITH FORCE-BALANCED COILS

S. TSUJI-IIO, Y. KOMATSU, J. KONDOH*, H. TSUTSUI, T. MURAKAMI,
K. SHIMADA, T. AKIYAMA, T. UEMURA, R. SHIMADA
Research Laboratory for Nuclear Reactors,
Tokyo Institute of Technology,
O-okayama, Meguro-ku, Tokyo 152-8550, Japan

Abstract

We manufactured a small pulsed tokamak with force balanced coils (FBCs), which balance the net centering force and the net radial hoop force due to the poloidal and toroidal current components, respectively. The centering force was demonstrated to be reduced by an order of magnitude compared with the computed one of the TF coils of the same dimension. The plasma current up to 10 kA was achieved by two-step FBC magnetization since the force-balanced winding provides not only toroidal magnetic fields but also the poloidal magnetic flux to induce the plasma current. The plasma column was well centered in the vacuum vessel within the time constant of shell effects of the vessel.

1. INTRODUCTION

The centering force of the toroidal field magnets is a vital issue concerning high-field tokamaks. We have devised force balanced coils (FBCs) [1, 2] which drastically reduce in-plane forces and have designed a sub-ignited tokamak reactor utilizing FBCs [3]. Since multi-pole helical coils are used to balance the net centering force and the net hoop force due to the poloidal and toroidal current components, respectively, the force-balanced winding provides poloidal magnetic flux. Thus FBCs can function both as toroidal field coils and as primary coils for ohmic heating, by which the coil systems of tokamaks can be simplified so that the construction of a pulsed high-field tokamak for fusion burn experiments would become easier. Although the winding is helical, poloidal components of the produced magnetic field can be designed to be negligible in the vacuum vessel.

We manufactured a small tokamak with FBCs to demonstrate the reduction of electromagnetic forces, plasma production and confinement with FBCs. To ramp up the plasma current stably avoiding stray-field effects due to eddy currents, we adopted a two-step coil excitation scheme which enables us to bring plasma breakdown when some strength of the toroidal field is established.

2. SMALL TOKAMAK DEVICE WITH FBC

The machine and nominal parameters of the small tokamak called as "TODOROKI-1", which means force balancing in Japanese, are summarized in Table I. The plasma minor radius is assumed to be that of a poloidal limiter. The maximum plasma current at 2 T is set by a safety factor at the plasma edge of 2.5. The force-balanced winding of TODOROKI-1 is illustrated in Fig. 1, in which a FBC composed of 6 turns of a cable is shown by darker hatch. The number of FBCs is eight and the winding pitch is five poloidal rotations round the torus. The winding pitch is modulated in such a way

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* Present address: Electrotechnical Laboratory, 1-1-4 Umezono, Tsukuba, Ibaraki 305-8568, Japan

TABLE I. PARAMETERS OF TODOROKI-1

Major radius	0.30 m
FBC minor radius	0.115 m
FBC inductance	0.65 mH
Plasma minor radius	0.055 m
Maximum toroidal field on axis	2 T
Maximum plasma current	40 kA
Capacitor bank	4 mF, 12.5 kV
	300 kJ

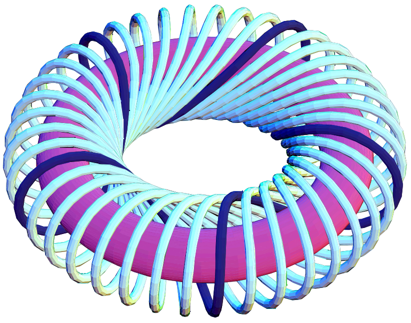

FIG. 1 FBC winding of TODOROKI-1.

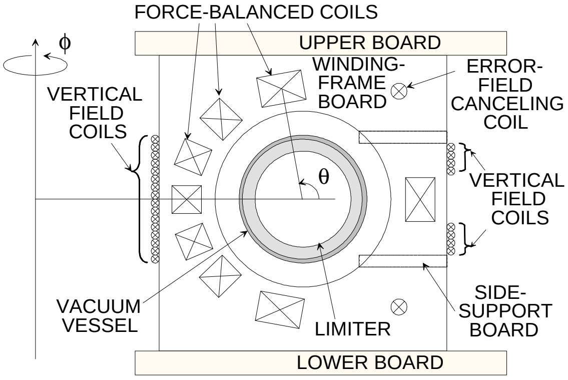

FIG. 2 Poloidal cross section of TODOROKI-1.

that the direction becomes more horizontal at the inner side of the torus, where the toroidal magnetic field is the strongest, to reduce the Lorentz force. The cable is made of 500 copper wires whose total cross section is 13 mm^2, and high-tension Kevlar of about 1 mm^2 for reinforcement. It was verified by a tensile test that the ultimate tensile strength of the cable rose from 270 kgf to 400 kgf without and with Kevlar, respectively, which implements the support of the hoop force in the minor radial direction.

The poloidal cross section of the device is shown in Fig. 2. The winding-frame board is made of glass-fiber reinforced plastics (GFRP) whose thickness is 15 mm. The upper and lower boards hold 40 winding-frame boards, and thereby support the centering force and the torsional force. The side-support boards also resist the torsional force. Since the centering force is drastically reduced with FBCs compared to that with conventional toroidal field coils, polymethyl methacrylate with a thickness of 30 mm can be used for the upper and lower boards. The FBCs of TODOROKI-1 have been successfully magnetized up to 1 T. Measurements with a load cell demonstrated that the centering force was reduced by an order of magnitude compared with the computed one of the TF coils of the same size [4].

Error-field canceling coils are connected in series with FBCs to minimize the error vertical field generated by the FBCs. The vacuum vessel made of 2.8-mm thick SS304 is toroidally insulated. Eight flux loops and a Rogowski coil are mounted on the outer surface of the vessel to measure poloidal fluxes and the plasma current, respectively. Sine and cosine coils with varying cross sections were wound along the bore of two winding-frame boards for FBCs to monitor plasma displacements. Two toroidal-flux loops were installed on the inside and outside of the vessel to check skin effects. 16 magnetic pick-up coils are mounted on the inside of the vessel to investigate plasma equilibrium.

3. PLASMA PRODUCTION AND CONFINEMENT EXPERIMENTS

The eight FBCs were connected in such a way that four sets of two-parallel FBCs are in series to double the induced one-turn voltage. The capacitor bank was divided into two blocks, one of which is discharged first to magnetize FBCs. The other block is discharged afterward to ramp up the plasma current when some strength of the toroidal field is produced and stray-fields due to eddy currents are reduced. The peak plasma current up to 10 kA was achieved by 7-kV charging of 1-mF and 3-mF capacitor blocks for the first and second coil excitations, respectively as shown in Fig. 3. The second FBC excitation at 2.4 ms, elapsed time from the first magnetization, was preceded by preionization at 2.3 ms to secure plasma breakdown. The delay in the B_T rise measured with the toroidal-flux loop was caused by poloidal eddy currents on the vessel. The cylindrical safety factor at the plasma edge was estimated to be 2.3 at the plasma current peak. From measurements with a Langmuir probe and a triple probe, the central electron temperature and the electron density at the current peak were found to be around 50 eV and about 2×10^{19} m^{-3}, respectively. The rise of the T_e signal before 2.4 ms was caused by the preionization.

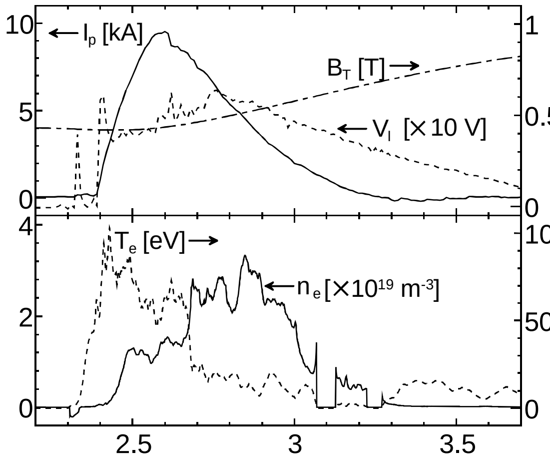

FIG. 3 Discharge waveforms by two-step FBC magnetization.

The one-turn loop voltage was rather high because the plasma was not clean enough; the base pressure of the vacuum vessel was 2×10^{-5} Torr and the visible spectral intensities of light impurities were comparable to those of hydrogen [5]. The high loop voltage may also be required to sustain the plasma current in the presence of error fields. Although the plasma had expired, the toroidal magnetic field at the vessel center reached 0.9 T at 4.3 ms.

The plasma pulse length appeared to be determined by the time constant of shell effects of the vessel since the plasma position was not actively controlled. An example of the traces of horizontal and vertical shifts of the plasma column evaluated with the sine/cosine coils are shown in Fig. 4 together with the plasma current waveform. The plasma displacement was cross-checked by computing the position of the current centroid through approximating the plasma current by six filaments [6] and linearly fitting to the pick-up coil data. The calculated plasma current from the filament approximation agrees with the measured one from the Rogowski coil quite well. The discrepancy between the horizontal positions estimated by the filament approximation and from the cosine coil may be explained by inadequate toroidal effect corrections to the latter estimation and the vulnerability of sine/cosine coils to stray fields. The plasma column was well centered in the vessel until the decay phase of the plasma current. The inward shift in the later phase of the discharge was caused by the increasing vertical field component generated by the FBCs since the FBC winding had not been optimized. We have devised the FBC winding pitch modulation which minimizes poloidal fields inside FBCs [2] after we designed TODOROKI-1. Improvement in the vertical field cancellation and preparation for pre-programmed vertical-field control are under way in addition to glow and ECR discharge cleaning of the vessel in order to prolong the discharge pulse length.

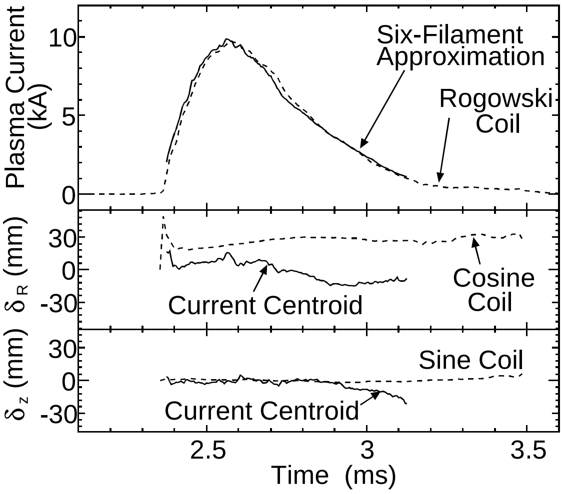

FIG. 4 Comparison of plasma current and plasma shifts evaluated by the six-filament approximation (solid traces) and from magnetic coils (broken traces).

4. CONCLUSIONS

We have devised force balanced coils (FBCs) which drastically reduce in-plane electromagnetic forces. Since multi-pole helical coils are used to balance the net centering force and the net hoop force, FBCs can function both as toroidal field coils and as primary coils for plasma current induction. Thus the FBC concept would simplify the coil systems of tokamaks.

We manufactured a small tokamak with FBCs to demonstrate the reduction of electromagnetic forces, plasma production and confinement with FBCs. The centering force was measured to be reduced by an order of magnitude compared with the computed one of the TF coils of the same dimension. The plasma current up to 10 kA was achieved by two-step FBC excitation.

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