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PLASMA PRODUCTION IN A TOKAMAK WITH FORCE-BALANCED COILS

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We have devised force balanced coils (FBCs) [1,2] which drastically reduce the centering force, a vital issue concerning high-field tokamaks, and have designed a sub-ignited tokamak reactor utilizing FBCs [3]. Since multi-pole helical coils are used to balance the net hoop force and the net centering force due to the toroidal and poloidal current components, respectively, the force-balanced winding provides poloidal magnetic flux. Thus FBCs can function both as toroidal field coils and as a central solenoid, which simplify the coil systems of tokamaks so that the construction of a pulsed high-field tokamak for fusion burn experiments would become easier. We manufactured a tokamak with FBCs to demonstrate the reduction of electromagnetic forces, plasma production and confinement in it. 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.

The machine and operational parameters of the small tokamak called as "TODOROKI-1", which means force balancing in Japanese, are summarized in Table 1. The force-balanced winding of TODOROKI-1 is illustrated in Fig. 1, in which a FBC is shown by darker hatch. The number of FBCs is eight and the winding pitch is five poloidal rotations round the torus. 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 overturning force. The side-support boards also resist the overturning 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 hoop force in the minor radius direction is supported by the tension of the cables. 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 dimension.

Table 1 Parameters of TODOROKI-1

Major radius	0.297 m
FBC minor radius	0.115 m
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

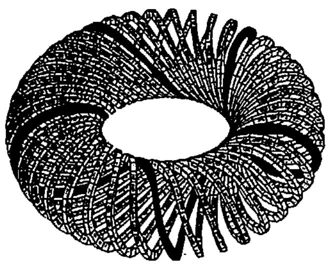

Fig. 1 FBC winding of TODOROKI-1

Error-field canceling coils are connected in series with FBCs to minimize the error vertical field generated by 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-current effects. 16 magnetic pick-up coils are mounted on the inside of the vessel to investigate plasma equilibrium.

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 at some strength of the toroidal field due to the first coil excitation. 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. From measurements with a Langmuir probe and a triple probe, the electron temperature and the electron density at the current peak were found to be around 20 eV and $(1\sim3) \times 10^{19}$ m^{-3}, respectively [4].

An example of the plasma current waveform is shown in Fig. 3 together with the traces of horizontal and vertical shifts of the plasma column evaluated with the sine/cosine coils. The plasma displacement was cross-checked by computing the position of the current centroid through approximating the plasma current by six filaments [5]. The calculated plasma current from the pick-up coils agrees with the measured one from the Rogowski coil quite well. The plasma column is well controlled at the center of the vessel within the time constant of shell effects. Thus we have demonstrated stable plasma confinement in the tokamak with FBCs.

Higher plasma current is expected by improving the decay index of vertical fields in addition to discharge cleaning through monitoring light impurities with a visible polychromator.

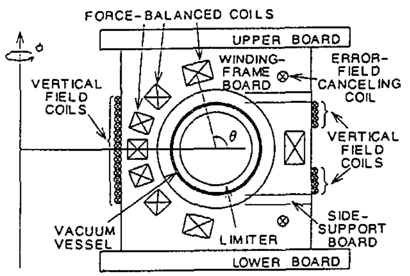

Fig. 2 Poloidal cross section of TODOROKI-1.

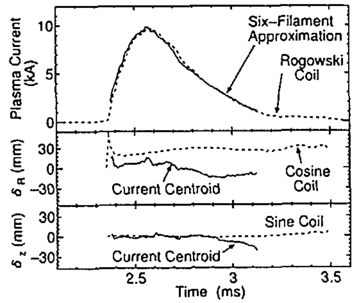

Fig. 3 Comparison of plasma current and plasma shifts from magnetic data.

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