Initial Results of Producing Tokamak in RELAX

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The safety factor and magnetic shear profiles play an important role in plasma confinement, particularly in cases of nearly zero or reversed magnetic shear. This may be closely related to the formation of internal transport barriers. We have upgraded the low-aspect ratio reversed field pinch (RFP) machine RELAX to produce tokamak plasmas, which will be used to investigate the physics of magnetic shear within a single machine. The preliminary measurements of the radial profile of the magnetic field have been conducted under different conditions in two separate experiments. The initial results indicate that standard tokamak and RFP plasmas are produced within a single machine due to an upgraded power supply that increased the toroidal field. This unique feature enables systematic studies of the physics of magnetic shear across the negative-to-positive region.

Keywords: magnetic shear, safety factor, low-aspect ratio, tokamak, reversed field pinch

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In magnetically confined plasma, the magnetic structure characterized by the safety factor (q) and its spatial derivative, i.e., the magnetic shear, is a crucial parameter due to its vital role in plasma stability. In recent years, non-monotonically increasing q profiles, such as nearly flat and reversed q profiles, have garnered significant attention for use in advanced scenarios for ITER operations [1]. These profiles, known as either zero or reversed magnetic shears, may improve plasma confinement through steady-state operation at high-plasma pressures and form internal transport barriers [2]. In addition, the simulations suggest the stiffness of the electron temperature profile in positive magnetic shear and the possibility of the electron temperature transport barrier in reversed magnetic shear [3]. Thus, while the relationship between turbulence and magnetic shear is studied theoretically; however, the underlying physics remain incompletely explored experimentally. To investigate this, we plan to systematically change the magnetic shear in two toroidal magnetic configurations: reversed field pinch (RFP) and tokamak plasmas.

In RFPs, the magnitude of the toroidal field B_ϕ is comparable to that of the poloidal field B_θ, and it is flipped at the plasma periphery. These characteristics cause the magnetic field line to twist firmly, which explains the strong negative magnetic shear. In contrast, the magnitude of B_ϕ in tokamaks is much larger than that of B_θ. Therefore, the magnetic shear is comparatively weak. This difference between RFP and tokamak configurations allows systematic studies of the effect of magnetic shear in toroidal plasmas.

In recent years, toroidal machines, which are initially designed for RFP research, have been utilized to study physics of tokamaks, such as runaway electrons [4] and the H-mode [5]. The power supply circuit for producing the B_ϕ of RELAX was upgraded to form tokamaks enabling comparative studies on the effect of magnetic shear profiles in a single machine, as shown in Fig. 1 (a). The aspect ratio of RELAX is the smallest among these machines [6]. Thus, RELAX should possess characteristics akin to those of spherical tokamaks, except that it has an iron core. In addition, due to the low-aspect ratio, RELAX can achieve

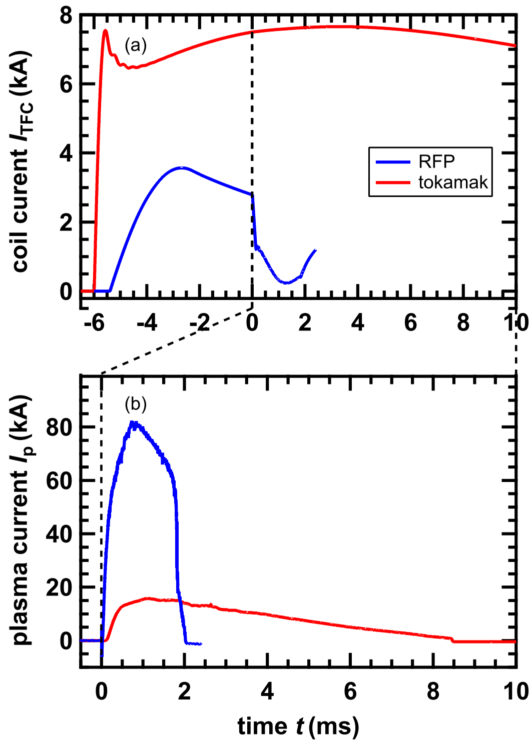

Fig. 1 Time evolution of (a) toroidal field coil current I_{TFC} and (b) plasma current for typical RFP and tokamak formed in the RELAX.

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extremely deep-reversal regions [7]. This uniqueness will enable a systematic investigation of the toroidal effect of the magnetic shear on transport.

A tokamak in RELAX with a plasma current of 20 kA and an edge safety factor of 4.0 yields $B_\phi \approx 0.08$ T, as shown in the red curve in Fig. 1 (b). To achieve this, the coils were reinforced against electromagnetic solid forces due to higher B_ϕ [8]. A power supply circuit for the tokamak operation is designed to increase B_ϕ. To the best of the author's knowledge, this is the first study to report the formation of tokamaks in RELAX. Measured radial profiles of B_ϕ and B_θ clearly indicate the successful formation of two different toroidal configurations in a single machine.

The profiles of B_ϕ and B_θ are measured using an insertable magnetic probe array that is installed from the top port of the chamber. The probe array consists of five pairs of pickup coils. Each pair of coils detects B_ϕ and B_θ, respectively. The distance between each pair of coils in all directions is 16 mm, corresponding to a normalized minor radius of $r/a = 0.064$, where a is the minor radius. In the experimental procedures, edge profiles of B_ϕ and B_θ in $0.75 < r/a < 1.0$ were investigated in detail. Figure 2 (a) illustrates the radial variation in the magnetic fields of the plasmas formed in the RELAX machine. The plots represent the time-averaged values of the measured B over flat-top time in a single shot. The flat-top time is when the plasma current exceeds 80% of its maximum value.

We also draw fitting curves for B_ϕ and B_θ to comprehend the radial variations in the measurements. The solid and dashed curves in blue in Fig. 2 (a) depict B_ϕ and B_θ for a typical RFP, respectively. We adopted the modified polynomial function model (MPFM), a typical model describing the equilibrium magnetic field of an RFP configuration [9]. The value of B_ϕ near the wall ($r = a$) is negative at approximately −10 mT. Further, B_ϕ turns out to be positive (≈ 68 mT) for a typical tokamak, as recognized from the solid red circles.

For simplicity, based on the assumption that the set of the toroidal field coils is an annular solenoid coil, B_ϕ is roughly estimated as $B_\phi(R) = \mu_0 N I_c / 2\pi R$, where R, μ_0, N, and I_c are the major radial coordinates, the permeability in vacuum, the number of coil turns, and the current flowing into the coil, respectively. All measured B_ϕ must be the same because the probe array is installed vertically from a top port at $R = R_0$. Regarding B_θ, the value is calculated based on the assumption that the toroidal plasma current j_ϕ distributes parabolically, that is, $j_\phi(r) = j_0\left[1 - (r/a)^2\right]$, where j_0 is the current density at the center of the plasma. Then, B_θ is given by $B_\theta(r) = \mu_0 j_0/(4a^4)(2a^2 r - r^3)$. The solid and dashed curves in red in Fig. 2 (a) are obtained, which show B_ϕ and B_θ, respectively. Further, it appears that B_ϕ is approximately seven times greater than B_θ.

Finally, we calculate the radial variation of q, denoted as $q(r)$, from the cylindrical approximation of the equation $q(r) = rB_\phi/(R_0 B_\theta)$. Figure 2 (b) illustrates $q(r)$ of a typical tokamak and the RFP. As seen from the blue curve for a typical RFP, $q(r)$ is less than unity, decreasing monotonically and becoming negative at the plasma periphery. For the red curve, $q(r)$ is greater than unity and monotonically increases from $q(0) \sim 2$ at the core to $q(a) \sim 4$ at the edge. These characteristics are similar to those of the standard tokamaks. Therefore, these results indicate that the RELAX has successfully formed both tokamak and RFP plasmas. The shadow region in Fig. 2 (b) will thus be the experimental target in RELAX, which includes a flat profile of $q(r)$ in the core.

In summary, we successfully produced circular tokamaks in RELAX to systematically study the physics of magnetic shear in toroidal plasmas within a single machine. The measured edge radial profiles of the magnetic fields exhibit typical tokamak profiles in RELAX, which were initially constructed to produce RFP plasmas. Such a unique feature offers insights into the dependence on the magnetic shear profile of transport and equilibrium properties on toroidal plasmas. In the next series of experiments, we will control macroscopic plasma instabilities, which provide regions akin to a low-q tokamak and a high-q one. In addition, we will measure $\int_\ell n_e d\ell$ and $T_e(0)$ by an interferometer and a Thomson scattering.

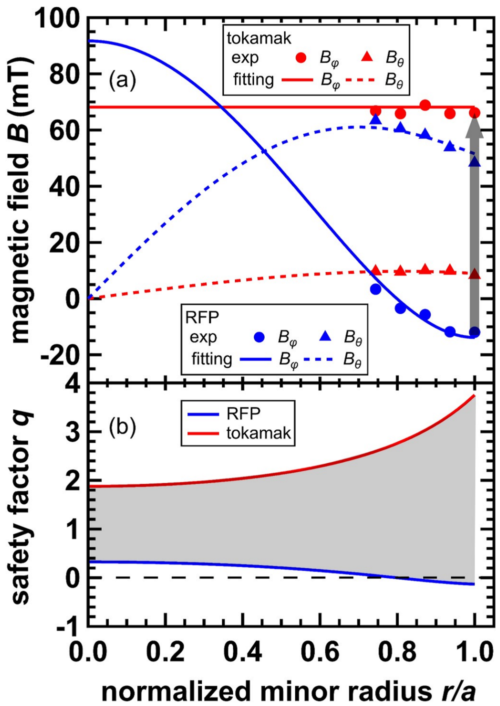

Fig. 2 Measured radial profiles of (a) magnetic fields and (b) safety factors of typical RFP and tokamak formed in the RELAX. The probe array moves vertically toward the center of the vacuum chamber ($R = R_0$), where R is the central radial coordinate, and R_0 is the major radius.

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