Power Supply Circuit for Dual Operation in Producing Tokamak and Reversed Field Pinch Plasmas in RELAX

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The power supply circuit attached to RELAX was upgraded to vary the magnitudes of the toroidal field on a single machine. The circuit enables dual operation—tokamak and reversed field pinch (RFP)—through a switch. Consequently, the upgraded circuit enables RELAX to operate within a wide range of safety factor profiles, encompassing tokamak and RFP plasmas. This upgrade enables the production of two distinct toroidal plasmas with comparable plasma currents, providing an opportunity to conduct systematic studies on the effect of magnetic shear in relatively low-density regions, where the two-fluid effect still represents a certain lack of mutual understanding.

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The magnetic structure in magnetized toroidal plasmas, characterized by the safety factor (q) and magnetic shear, is crucial for developing high-temperature plasmas. The evolution of the q profile arises from inherently stable dynamics but requires precise control to prevent magneto-hydrodynamic (MHD) instabilities. An adequate q profile is required for good confinement and MHD stability in magnetically confined plasmas [1]. Changes in magnetic shear can greatly modify plasma confinement characteristics and turbulence behaviors. For instance, the local transport analysis indicates the feature of a transient reduction in transport, and low-wavenumber turbulence appears to be suppressed when the magnetic shear is reduced [2]. Moreover, non-monotonically increasing q profiles of zero and reversed magnetic shear have recently gained considerable interest [3]. These profiles appear to maintain a steady high plasma pressure and facilitate the formation of internal transport barriers, thereby improving plasma confinement [4]. To explore these effects systematically, we planned to systematically vary the magnetic shear profile in a single machine [5, 6].

Tokamaks feature a strong toroidal field (B_ϕ) that exceeds their poloidal field (B_θ) induced by the plasma current (I_p). Consequently, tokamaks are characterized by a high B_ϕ with a relatively low I_p. In contrast, in reversed field pinches (RFPs), the B_ϕ generated by the external coils is much lower than B_θ. Furthermore, the polarity of B_ϕ of RFP is reversed between the plasma core and the periphery. The characteristic means that RFPs are characterized by a low B_ϕ with a relatively high I_p. The relationships between the strengths of B_ϕ and I_p are opposite. The difference requires adjusting the magnitude of B_ϕ to facilitate comparative experiments with comparable I_p on the same single machine.

Therefore, we upgraded the toroidal coil system in RELAX, initially designed for low-aspect ratio RFP research, to enable tokamak operation [5]. Our first study achieved tokamak configuration with lower plasma currents of 16 kA, which is less than those flowing RFP plasmas in RELAX [6]. At least the RELAX-RFP plasma flows I_p of 40 kA. The previous paper did not provide specifications for the power supply circuit to produce the tokamak configuration. Subsequently, the power supply circuit was upgraded to stronger B_ϕ using a switching technique to produce RFP or tokamak plasmas in RELAX. This paper shows the method.

In RFP operation, the power supply circuit reverses B_ϕ at the plasma periphery by feeding current in the opposite direction via the toroidal field coil (TFC). However, tokamak operations require an increase in magnitude, not a reversal B_ϕ. This indicates that B_ϕ must be increased to 0.15 T to produce a typical tokamak plasma with $q \sim 3$ at the plasma edge. To achieve this, the TFC current (I_{TFC}) must be increased to 15 kA, approximately double the trial for making the first tokamak configuration. The upgraded circuit supports the higher current and, consequently, the B_ϕ increases to accommodate these requirements. This paper presents for the first time the upgraded power supply circuit designed to generate B_ϕ in two operating modes to produce both tokamak and RFP plasmas with comparable I_p in RELAX.

The power supply circuits for generating B_ϕ in RELAX equip a power crowbar circuit containing capacitors C_H (charged with high voltage, small capacitance) and C_L (charged with low voltage, large capacitance), crowbar diodes, and a load coil. The C_H facilitates a rapid current increase, while C_L ensures a gradual current decay. The crowbar diodes prevent a reverse current flow into the TFC and negative

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charging of the capacitors. They maintain a non-oscillatory current with unipolar damping for quasi-steady-state current flow through the TFC. Figure 1 shows the power supply circuit used to generate B_ϕ in RELAX. The circuit is divided into three sections. The upper and middle sections are utilized to apply the biased and reversed toroidal fields ($+B_\phi$ and $-B_\phi$) during the RFP operation, respectively. The lower section generates $+B_\phi$ specifically for the tokamak operation. The upper circuit generates $+B_\phi$ for RFP operations to ensure complete penetration into the vacuum chamber prior to plasma ignition. Simultaneously, upon plasma ignition, the middle circuit reverses the current through the TFC to apply $-B_\phi$, enhancing B_ϕ reversal at the plasma periphery.

The lower circuit designed for tokamak operation is also shown in Fig. 1. This circuit feeds more forward current into the TFC to generate $+B_\phi$. Through a DC-DC converter, C_H is charged up to 10 kV with a maximum current of 25 mA. The set of C_H, typically set to 800 μF and connected in four parallels, is less than that used for RFPs to achieve a steep increase in current. C_L is charged using a DC power supply to 850 V with a charge current of 3.6 A. These C_L are connected in 115 parallel and 2 series, totaling approximately 0.5 F to maintain B_ϕ during discharge. The crowbar diodes use a five-series diode stack to increase the operating voltage. A stack of three-series thyristors (SCRs) serves as the switch. TFC is the load coil in all circuits. A brass bus bar in the green dashed box shown in Fig. 1 switches the connection between the TFC and the circuit for RFP or tokamak operations.

For each operation, we measure I_{TFC} and the toroidal field at the plasma edge ($B_{\phi a}$) over time. To produce RFPs, I_{TFC} peaks at 2.5 kA before plasma ignition and then changes its polarity at $t = 0$ ms. The value of I_{TFC} reaches -0.7 kA, as depicted by the blue curves in Fig. 2(a). Consequently, $B_{\phi a}$ reaches 20 mT before plasma ignition and then reverses to -10 mT during RFP formation.

On the other hand, the red curves illustrated in Figs. 2(a) and (b) depict the time evolution of I_{TFC} and $B_{\phi a}$ during the tokamak operation, respectively. The typical charging voltages of C_H and C_L are set to 6.7 kV and 700 V, respectively. Consequently, the maximum I_{TFC} increases to 15 kA, approximately six times that during the RFP operation. This brings the average toroidal field in a poloidal cross-section to 150 mT, and $B_{\phi a}$ reaches 130 mT. The decay in current is more gradual because of the larger C_L. Defining the flat-top time as a current that exceeds 80% of its maximum value, the flat-top time is approximately 9 ms. Therefore, the designed circuit fulfills the requirements for tokamak operation.

Finally, we produce tokamak and RFP plasmas using those circuits in RELAX. The red and blue curves shown in Fig. 2(c) represent the typical I_p of the tokamak and RFP plasmas, respectively. This result demonstrates that the single machine successfully formed tokamak and RFP plasmas with a magnitude comparable to I_p.

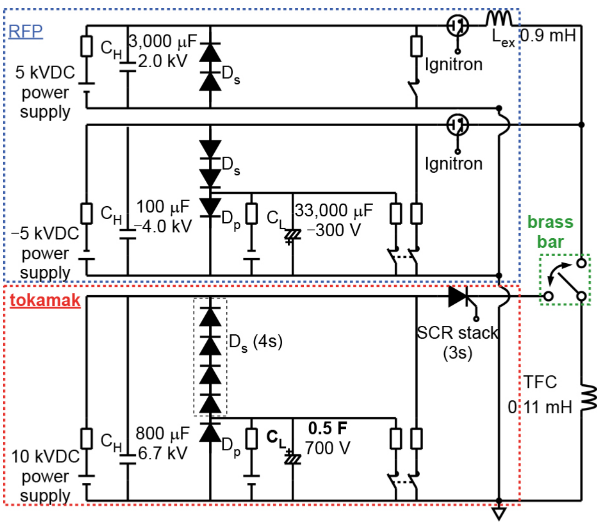

Fig. 1. Diagram of power supply circuits for generating the toroidal field in the RELAX. The circuits surrounded by blue and red dashed lines are used for RFP and tokamak operations, respectively. The green dashed line surrounds the brass bus bar that switches these circuits.

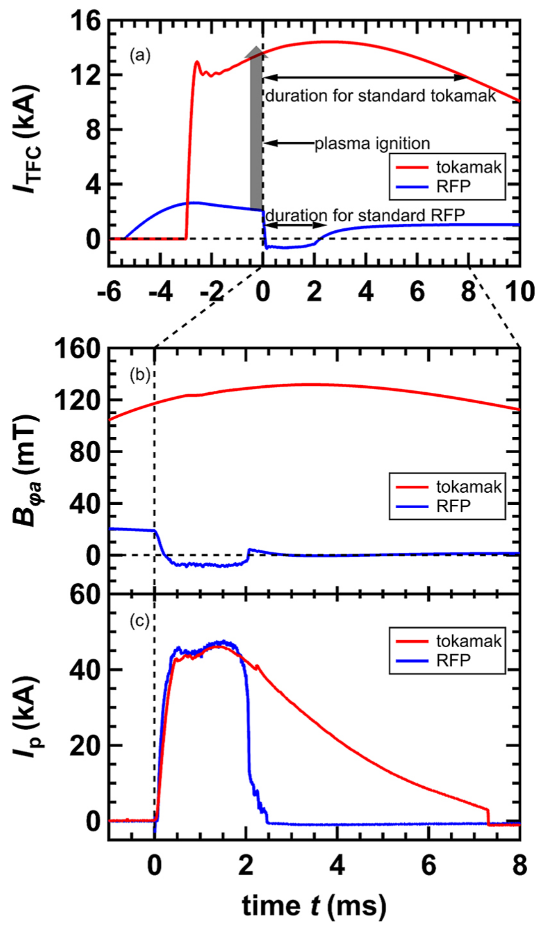

Fig. 2. (a) Time evolution of the toroidal field coil current (I_{TFC}), (b) the toroidal field at the plasma edge ($B_{\phi a}$), and (c) plasma current (I_p) during RFP and tokamak operations. The reference time ($t = 0$) is the plasma ignition time. The currents start to flow into the TFC before plasma ignition. The typical edge safety factor is −0.12 and 2.5 for RFP and tokamak plasmas, respectively.

In summary, the upgraded power supply circuit, which increases the magnitude of B_ϕ without reversal, enables the production of tokamak plasmas with comparative I_p in RFP. The circuit that reverses B_ϕ and generates low B_ϕ for RFP operation and the circuit that generates high B_ϕ for tokamak operation can be switched using a single switch. These techniques will help produce tokamaks and RFPs in RFP machines. Moreover, this upgrade enables us to systematically explore the q profile and its magnetic shear effect on transport and equilibrium in various magnetic structures of toroidal plasmas with a relatively low density. This is expected to help better clarify how different magnetic structures contribute to the dynamics of MHD activity and the formation of an internal transport barrier [7]. Consequently, future studies will compare plasma characteristics between tokamaks and RFPs with comparable I_p, providing more precise insights into how different magnetic shear profiles impact plasma transport and equilibrium.

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