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Design of rotating resonant magnetic perturbation coil system in the STOR-M tokamak

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HIGHLIGHTS

- Static RMP fields were successfully produced in STOR-M by an ($l=2$, $n=1$) helical coil.
- A new RMP system, consisting of sets of saddle coils powered by an AC power supply, is being designed to generate rotating RMP fields.
- The total magnetic field produced by the coil system was calculated at the $q=2$ surface.
- The saddle coils generate a dominant (2, 1) mode with sideband (2, 3) and (2, 5) modes.
- An H-bridge circuit will be utilized to drive an AC current through the saddle coils.

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ABSTRACT

The interaction between resonant magnetic perturbations (RMP) and plasma is an active topic in fusion energy research. RMP involves the use of radial magnetic fields generated by external coils installed on a tokamak device. The resonant interaction between the plasma and the RMP field has many favorable effects such as suppression of instabilities and, under certain conditions, improvement of discharge parameters in tokamaks. The RMP technique has been successfully implemented in the STOR-M tokamak. A set of ($m=2$, $n=1$) helical coils carrying a current pulse was used to study the effects of RMP on magnetic islands, plasma rotation, and other edge plasma parameters. A new RMP system is being developed for the STOR-M tokamak. The system consists of a number of external saddle coils distributed in the poloidal and toroidal directions and powered by AC power supplies to generate a rotating RMP field. Numerical simulations have been carried out to calculate several parameters for the new RMP system such as the magnetic field and the dominant modes generated by the coils. The dominant mode generated by the new RMP coil system may be tuned to (2, 1) with significant contributions from (2, 3) and (2, 5) modes.

1. Introduction

Resonant magnetic perturbations (RMP) [1] have drawn a great deal of attention through their favorable effects on tokamak plasmas. RMP have several well-established applications in tokamaks. These applications include edge localized mode (ELM) mitigation [2], error field correction [3], edge transport modification [4], tearing mode suppression [5], runaway electron mitigation [6], and plasma rotation control [7].

RMP involves the use of static or rotating radial magnetic fields generated by external coils installed on a tokamak device. One of the attractive features of RMP is the mode stabilization which has been successfully demonstrated in many tokamaks. Mode stabilization leads to a significant reduction in frequency and amplitude of tearing mode fluctuations. It has been found that applying a current pulse through a set of pre-configured coils with the same helicity as the magnetic islands in a tokamak plasma suppresses the magnetic fluctuations, provided that the coil current is below the mode-locking threshold [1]. However, if the applied RMP field is too large, the islands in plasma will grow and mode locking may occur [8].

The RMP technique has been successfully implemented in the Saskatchewan Torus-Modified (STOR-M) tokamak. The RMP fields

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are generated in STOR-M by driving two static current pulses with equal magnitude and opposite direction through two sets of helical windings with an ($l = 2$, $n = 1$) configuration, where l denotes the poloidal number of helical windings and n is the toroidal mode number of the external windings. The two helical windings are poloidally separated by 90° and installed against the outer surface of the vacuum chamber at a radius of 17 cm.

During previous experiments in STOR-M, it has been observed that tearing modes [9] can be controlled by the RMP fields. The tearing mode stabilization is characterized by a significant reduction in amplitude and frequency of magnetohydrodynamic (MHD) fluctuations. In more recent experiments, it has been found that the mode stabilization is accompanied by a substantial change in the toroidal plasma flow [10]. The modification of toroidal flow has been studied at different magnitudes of RMP field. After application of RMP with moderate current amplitude, the toroidal flow velocity of impurity ions slows down in the plasma core region. Flow reversal has also been observed at higher RMP currents.

The current RMP system in STOR-M creates only a stationary magnetic field that does not rotate with the magnetic islands. Therefore, a new RMP system is being developed to generate rotating RMP fields. The advantage of producing a rotating RMP with variable phase and frequency is to stabilize the targeted magnetic islands without mode locking which is one of the main causes for plasma disruptions. AC RMP coils with mode-locking prevention feedback systems have been successfully utilized in several tokamaks such as TEXTOR [11] and J-TEXT [12] tokamaks.

This paper is organized as follows. Section 2 provides an overview of the proposed design for the new RMP system. Section 3 highlights the results of numerical analysis of the magnetic field generated by the new saddle coils. The mode spectrum produced by the new RMP coil system is presented in Section 4. The circuit analysis and considerations for the RMP system are discussed in Section 5. A summary is given in Section 6.

2. Conceptual design

A new design of RMP system is currently being developed for STOR-M. The new system consists of a power supply, an H-bridge circuit, and saddle coil system. The saddle coil system consists of 4 sets of external saddle coils installed at different toroidal location on STOR-M. Each coil set is comprised of 4 poloidal saddles placed on top, bottom, low and high field sides at a radius of 17 cm from the plasma center.

Fig. 1 is a top view of the STOR-M tokamak with the saddle coils installed on it. The top and bottom coils are identical and chosen to be isosceles trapezoidal. Furthermore, the saddle coils located at low and high field sides are two rectangular coils with different sizes. This coil arrangement will be able to target the (2, 1) tearing mode which is the dominant MHD mode in STOR-M.

The dimensions of the saddle coils, listed in Table 1, are determined based on the space available on the vacuum chamber of STOR-M. The geometric parameters a and b are the lengths of two adjacent sides of the trapezoidal coils and γ is the acute base angle. Similarly, for the rectangular coils, a and b are the lengths of the sides and all angles are 90°. These parameters will be used for the numerical simulations in the upcoming sections.

The coil system will be powered by the DC power supply of the existing RMP system. The power supply consists of a 50 mF, 450 V fast capacitor bank (for fast current ramp-up) and a 480 mF, 200 V slow bank (for maintaining the current flat-top). An H-bridge will be used to produce an alternating current from the DC power supply. By switching the voltage across a resonant load (i.e., the inductive saddle coils and a capacitor) at its natural frequency, from V to −V, the current through the load will alternate. Driving an

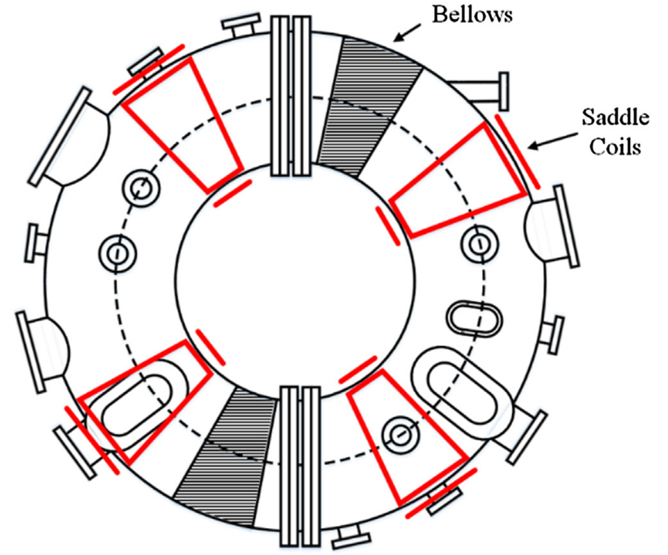

Fig. 1. Top view of STOR-M showing the location of the saddle coil sets.

AC current through the saddle coils will generate a rotating RMP field with variable phase and frequency. The operational frequency of the new system will be in the range of 10–30 kHz which is the typical rotating frequency of MHD modes in STOR-M.

As mentioned earlier, the saddle coils will be installed externally on the vacuum chamber of STOR-M, which is made of stainless steel (304L alloy) with a thickness of 4 mm and cut-off frequency of 11 kHz. As a result, the radial RMP field generated by the coils will be attenuated by the skin effect. The skin depth at the operational frequency of the new RMP system (10–30 kHz) is between 2.4 mm and 4.2 mm, resulting in a field attenuation in the range of 60–80%. This attenuation will be accounted for by either installing in-vessel saddle coils or driving larger AC current through the coils.

3. Magnetic field calculations

Numerical simulations have been carried out to calculate the total magnetic field in 3D space generated by the new RMP system. The magnetic field due to a single saddle coil can be determined using the Biot-Savart law for a line current as:

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \int_C \frac{I d\mathbf{l} \times \hat{\mathbf{r}}'}{|\mathbf{r}'|^2} \quad (1)$$

where I is the current, C is the curve describing the wire, and $d\boldsymbol{l}$ is the tangent vector to the curve C at r'. Eq. (1) uses the thin wire approximation which assumes that the current is concentrated at the center of the wire. This approximation is sufficient as the magnetic field is calculated at locations away from the wire (i.e. a distance greater than the thickness of the wire).

The calculations of magnetic field are carried out for a single trapezoidal or rectangular coil in the coil coordinates. After the magnetic field is calculated, it is rotated and translated into the torus coordinates (r, θ, ϕ). The magnetic field in the torus coordinates at a point $\boldsymbol{r}$ is given by:

$$\mathbf{B}(\boldsymbol{r}) = \mathrm{M_c}\mathbf{B_c}(\mathrm{M_c^{-1}}(\mathbf{r} - \mathbf{r_c})) \quad (2)$$

where M_c is a rotation matrix from coil coordinates to torus coordinates, and $\mathbf{B}_c$ is the magnetic field calculated in the coil reference frame, assuming the coil is centered at r_c.

The contribution of each individual coil to the magnetic field can be calculated by Eqs. (1) and (2) and added up to obtain the total magnetic field. Fig. 2 shows a snapshot of the total radial magnetic

Table 1
Dimensions of saddle coils.

	Isosceles Trapezoidal Coils	High-Field Rectangular Coil	Low-Field Rectangular Coil
a	0.13 m	0.13 m	0.20 m
b	0.20 m	0.20 m	0.20 m
γ	80°	90°	90°

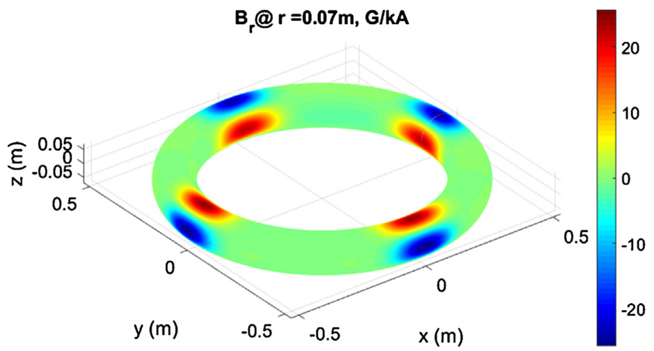

Fig. 2. The radial magnetic field produced by the saddle coils at the (2, 1) resonance surface (r = 7 cm).

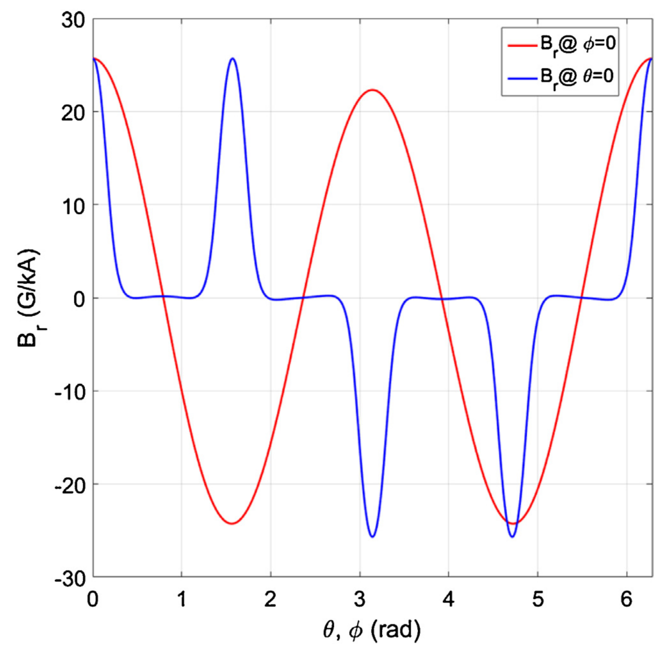

Fig. 3. The radial magnetic fields in the poloidal and toroidal planes at the (2, 1) resonance surface (r = 7 cm).

field generated by the saddle coils in the torus coordinates. The coils are fed by an AC current (±1 kA) and assumed to be located outside the vacuum chamber at r = 17 cm from the plasma center. The total field is calculated at r = 7 cm which is the location of the q = 2 resonance surface in STOR-M as suggested by previous calculations of the safety factor profile in STOR-M [10]. The peak radial magnetic field generated at the q = 2 surface is about 25G/kA.

4. Mode spectrum

In order to calculate the mode spectrum produced by the saddle coils, the radial magnetic field has to be expressed in the same form as the radial magnetic field of MHD modes. The radial magnetic field generated by the RMP saddle coils can be written as:

$$B_r\left(\theta, \phi, t\right) = \sum_{n,m} B_{r0mn} \cos\left(m\theta - n\phi + \omega t\right) \tag{3}$$

where B_{r0mn} is the amplitude of m and n modes at r_0. The magnetic field in Eq. (3) can be expressed for poloidal and toroidal modes separately. For the poloidal modes the magnetic field for a specific value of ϕ and t is given by:

$$B_r\left(\theta, \phi_0, t_0\right) = \sum_{m} \left(B_{r0m,c} \cos\left(m\theta\right) + B_{r0m,s} \sin\left(m\theta\right)\right) \tag{4}$$

where $B_{r0m,c}$ and $B_{r0m,s}$ are amplitudes of the cosine and sine coefficients (Fourier series coefficients) for the m^{th} mode. Similarly, the magnetic field for the toroidal modes for a specific value of θ and t is given by:

$$B_r\left(\theta_0, \phi, t_0\right) = \sum_{n} \left(B_{r0n,c} \cos(n\phi) + B_{r0n,s} \sin(n\phi)\right) \tag{5}$$

The radial magnetic fields at fixed ϕ, θ and t are shown in Fig. 3 which were calculated in Section 3. Finally, the Fourier series coefficients for the poloidal modes can be calculated from:

$$B_{r0m,c} = \frac{1}{\pi} \int_0^{2\pi} B_r\left(\theta, \phi_0, t_0\right) \cos\left(m\theta\right) d\theta \tag{6}$$

$$B_{r0m,s} = \frac{1}{\pi} \int_0^{2\pi} B_r\left(\theta, \phi_0, t_0\right) \sin\left(m\theta\right) d\theta \tag{7}$$

and the toroidal Fourier coefficients take a similar form. The mode spectrum generated by the saddle coils can be seen in Fig. 4. The figure shows the normalized amplitude of each mode calculated by Eqs. (6) and (7). It is clearly seen that there is a strong (2, 1) mode generated by the saddle coil system. The (2, 1) mode represents about 33.17% of the total spectrum amplitude. The (2, 3) and (2, 5) sideband modes also significantly contribute to the mode spectrum by 32.9% and 27.86%, respectively. The coil system can be tuned to generate other modes such as (1, 1), (2, 2), and (1, 2). However, generating higher (n, m) modes will require larger numbers of saddle coils.

5. Circuit analysis

An AC driving circuit is currently being developed for the new RMP system. An AC current, as opposed to a DC current, is used in order to vary the phase differences between the coils. The phase differences will allow the magnetic field created by the saddle coil arrangements to rotate along with the MHD modes, thereby more effectively controlling these modes [12]. As mentioned earlier, the frequency range of the modes is in the range of 10 kHz to 30 kHz, and will be the same range of frequencies which will be considered for operation of the driving circuit.

A common method for producing an alternating current from a DC voltage source is the implementation of a single phase H-bridge invertor. A schematic of an H-bridge circuit is shown in Fig. 5. Switches Q1 and Q4 operate at the same frequency, and are out of

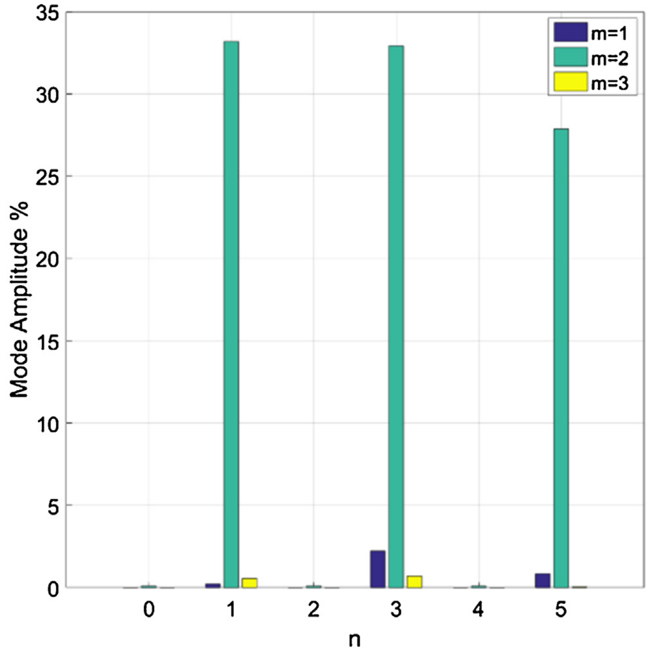

Fig. 4. Mode spectrum generated by the saddle coils.

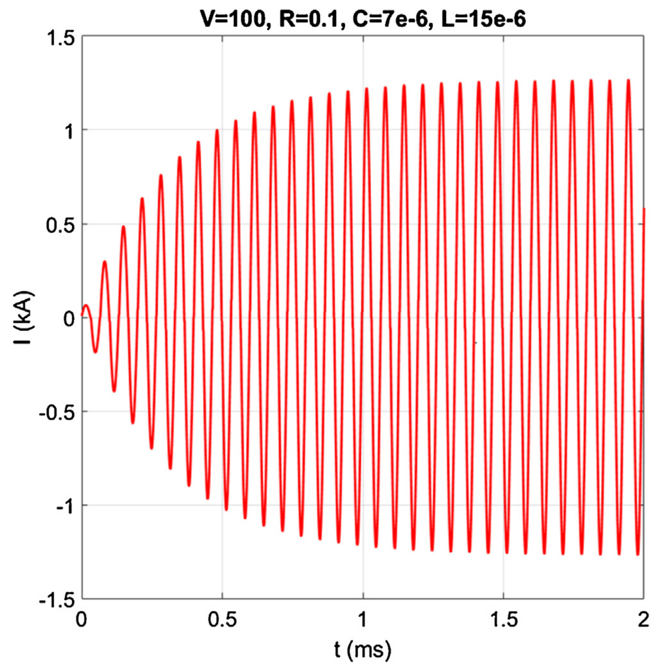

Fig. 6. The current waveform driven through the saddle coil.

phase with switches Q2 and Q3, which also operate in tandem. This switching causes the voltage across the load (i.e., saddle coils) to alternate between V and −V at the same driving frequency as the switches. Subsequently, the current through the load will alternate. IGBT power modules are preferred to be used as switches due to the high voltage and current ratings.

The RMP coil system can be treated as a series RLC circuit. For an underdamped series RLC load, the driving frequency can be approximated by the damped natural frequency (ω_d) of the load which is given by:

$$\omega_d = \sqrt{\omega_0^2 - \alpha_0^2} = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \tag{8}$$

where R, L, and C are, respectively, the resistance, the inductance, and the capacitance of the saddle coil. The current through the saddle coil will decay over time as the capacitor charges. To counter this effect, the voltage polarity has to be reversed at the point of current zero-crossing. Since, the charge on the capacitor is not zero at the time when the voltage switches the polarity, the initial conditions will be altered and the amplitude of the current will change after each zero crossing until a steady state is achieved.

The H-bridge circuit shown in Fig. 5 has been simulated to estimate the current driven though the saddle coil. Fig. 6 shows the

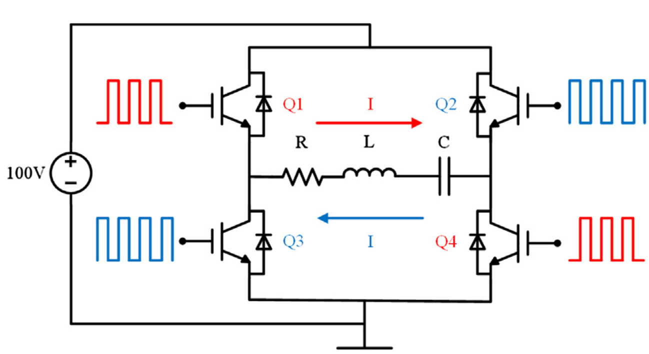

Fig. 5. A schematic of H-Bridge circuit.

resultant current waveform through a coil with 100mΩ resistance and 15 μH inductance connected in series to a 7 μF capacitor. For these given values, the damped natural frequency of the system is about 15 kHz. The current reaches a steady-state value of 1.25 kA after 2 ms when the power supply is set at 100 V. It should be noted that the switching frequency of IGBT modules must match ω_d of the circuit. The system frequency can be tuned by varying the capacitance C.

6. Summary

The STOR-M tokamak is currently equipped with an RMP system that produces static RMP fields by (l = 2, n = 1) helical coils. The stationary RMP field was successfully used to suppress MHD instabilities as well as to modify the plasma rotation and edge plasma profiles. An improvement on this design is to be able to produce modes which rotate at the same frequency as the instabilities in the plasma.

A conceptual design for a new RMP system is currently being developed for STOR-M to generate rotating RMP fields with variable phase and frequency. The new system consists of sets of saddle coils installed at different poloidal and toroidal locations on STOR-M. An H-bridge circuit is utilized to drive an AC current through the saddle coils.

Numerical simulations were carried out to calculate the total magnetic field and the mode spectrum produced by the coil system at the q = 2 surface. It was found that the saddle coils generate a dominant (2, 1) mode with a substantial contribution from the sideband (2, 3) and (2, 5) modes. Circuit analysis was also conducted for the new RMP system to determine the optimal parameters for the system as well as to calculate the current driven through the saddle coils.

Acknowledgments

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References

[1] T.C. Hender, et al., Effect of resonant magnetic perturbations on COMPASS-C tokamak discharges, Nucl. Fusion 32 (12) (1992) 2091–2117.
[2] T.E. Evans, et al., Suppression of large edge-localized modes in high-confinement DIII-D plasmas with a stochastic magnetic boundary, Phys. Rev. Lett. 92 (23) (2004) 235003, 1–4.
[3] R.J. Buttery, et al., Error field mode studies on JET, COMPASS-D and DIII-D, and implications for ITER, Nucl. Fusion 39 (11Y) (1999) 1827–1835.
[4] M.V.A.P. Heller, et al., Edge turbulence spectrum alterations driven by resonant fields, Nucl. Fusion 35 (1) (1995) 59–67.
[5] L. Frassinetti, et al., Resonant magnetic perturbation effect on tearing mode dynamics, Nucl. Fusion 50 (3) (2010) 035005, 1–13.
[6] M. Lehnen, et al., Suppression of runaway electrons by resonant magnetic perturbations in TEXTOR disruptions, Phys. Rev. Lett. 100 (25) (2008) 255003, 1–4.
[7] K.H. Finken, et al., Toroidal plasma rotation induced by the dynamic ergodic divertor in the TEXTOR tokamak, Phys. Rev. Lett. 94 (1) (2005) 015003, 1–5.
[8] Q. Hu, et al., Effect of externally applied resonant magnetic perturbations on resistive tearing modes, Nuclear. Fusion 52 (8) (2012) 083011, 1–11.
[9] S. Elgriw, et al., Control of magnetic islands in the STOR-M tokamak using resonant helical fields, Nucl. Fusion 51 (11) (2011) 113008, 1–10.
[10] S. Elgriw, et al., Modification of plasma rotation with resonant magnetic perturbations in the STOR-M tokamak, Plasma Phys. Controlled Fusion 58 (4) (2016) 045002, 1–11.
[11] T. Zhang, et al., Influence of rotating resonant magnetic perturbation on the plasma radial electric field on TEXTOR, Nucl. Fusion 52 (7) (2012) 074013, 1–9.
[12] B. Rao, et al., First observation of rotation acceleration of magnetic island by using rotating resonant magnetic perturbation on the J-TEXT tokamak, Plasma Phys. Controlled Fusion 55 (12) (2013) 122001, 1–5.