Effects of Resonant Helical Field on Toroidal Field Ripple in IR-T1 Tokamak

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Abstract. The toroidal magnetic field which is created by toroidal coils has the ripple in torus space. This magnetic field ripple has an importance in plasma equilibrium and stability studies in tokamak. In this paper, we present the investigation of the interaction between the toroidal magnetic field ripple and resonant helical field (RHF). We have estimated the amplitude of toroidal field ripples without and with RHF (with different $q = \frac{m}{n}$) ($m = 2$, $m = 3$, $m = 4$, $m = 5$, $m = 2$ & $n = 1$) using “Comsol Multiphysics” software. The simulations show that RHF has effects on the toroidal ripples.

1. Introduction
Tokamak is an acronym developed from the Russian words “Toroidalnaya Kamera i Magnitnaya Katushka” which means “toroidal chamber with magnetic coils”. As the name suggests, it is a magnetic confinement device with toroidal geometry [1]. In Tokamak, the outward force of the plasma pressure is balanced by the magnetic field. The magnetic field is created by toroidal coils, primary coils, and vertical coils. Toroidal coils generate the magnetic toroidal field. The plasma current produces the poloidal magnetic field. Thus, the combination of toroidal and poloidal fields give rise to magnetic field lines that have a helical trajectory around the torus. The magnetic field ripple which is made by toroidal coils has an importance in plasma equilibrium and stability studies. The magnetic field in an axisymmetric tokamak is Comprised an externally produced toroidal component,

$$B_\phi = B_0 \frac{1}{1 + \left(\frac{r}{b}\right) \cos \phi} \quad (1)$$

If the toroidal field is generated by N separate coils, its magnitude is no longer independent of the variable $\phi$ since the magnetic field will be slightly stronger within the plane of the coils than between the coils. This variation can be represented by the addition of a small perturbation to the toroidal field component, $\Delta B$ [2].

$$\frac{\Delta B}{B_0} = \delta(r, \Theta) \cos N \phi \quad (2)$$

This discrepancy causes the toroidal field fluctuation named Toroidal Ripple. Low fluctuations of magnetic field cause the better confinement and plasma stability. Also, the nonlinear evolution of magnetohydrodynamical instabilities makes the plasma cool within milliseconds which create the runaway electrons, and finally, confinement loss happens which named major disruption. One way to reduce the plasma disruptions in circular cross section tokamaks is to use the resonance helical filed
(RHF), which is caused by a winding coil that wrapped around the chamber torus. RHF can postpone the major disruptions [3], flatting the plasma current [4, 5], decreases the Shafaranov shifts [6], plasma displacements and amplitude of magnetic field fluctuations [5], improve the plasma confinement and increase the confinement time [4, 5]. Some experimental and theoretical studies have been done such as chaotic structure. In this paper, we present the simulation study on the effects of RHF on the toroidal field in the IR-T1 Tokamak which is the small, low beta and large aspect ratio circular cross section tokamak. Picture of the IR-T1 Tokamak, plotted by Comsol Multiphysics software in shown in figure 1.

![Figure 1. Circular cross section of the IR-T1 tokamak simulated by Comsol Multiphysics. The chamber has major and minor radius 45 cm and 12.5 cm, respectively. 16 O-shape TF coils and 7 primary coils are designed with the major radius of 17.5 cm and the minor radius of 2.5 cm. 2 vertical coils with the major radius of 45 and the minor radius of 5 cm. Also, we assume that there is no plasma current ($I_p=0$).](image)

2. Modelling details

2.1. Toroidal field ripple

Toroidal coils cause the toroidal field which calculated by this equation:

$$B = \frac{\mu NI}{2\pi R}$$

In this equation, $R$ is the major radius of tokamak and $N$ is the number of toroidal coils, $I$ is the current in the toroidal field coils, $\mu = 4\pi \times 10^{-7} \text{ H/m}$. Toroidal field lines fluctuation is called the Ripple. The main reason of this ripple is the finite number of toroidal field coils with space between them which is large enough to effects magnetic field intensity and causes the undulation. The toroidal ripple may cause the reduction of confinement and plasma stability. RHF coils are the external coils which are similar to the toroidal field coils that apply the
resonance magnetic perturbation to the plasma edge. This coil effects on toroidal field ripple due to its $q$ factor, $q = m/n$ with $m$ and $n$ the toroidal and poloidal rotation around the tokamak chamber respectively [7].

2.2. Comsol Multiphysics
COMSOL Multiphysics® is a general purpose software platform, based on advanced numerical methods, for modeling and simulating physics-based problems. COMSOL Multiphysics, enable to account for coupled or multiphysics phenomena, also further expanding the simulation platform with dedicated physics interfaces and tools for electrical, mechanical, fluid flow, and chemical applications. Using COMSOL Multiphysics provides a significant amount of physics modeling functionality, including multiphysics ability. By adding application-specific modules, the modeling power is increased with dedicated tools for electrical, mechanical, fluid flow, and chemical applications. COMSOL Multiphysics includes a set of core physics interfaces for common physics application areas such as structural analysis, laminar flow, pressure acoustics, transport of diluted species, electrostatics, electric currents, heat transfer, and Joule heating. These are simplified versions of a selected set of physics interfaces available in the add-on modules. For arbitrary mathematics or physics simulations, where a preset physics option is not available, a set of physics interfaces is included for setting up simulations from first principles by defining the equations. Several partial differential equations (PDE) templates make it easy to model second-order linear or nonlinear systems of equations. By stacking several equations together, you can also model higher-order differential equations. These equation-based tools can further be combined with the preset physics of COMSOL Multiphysics or any of the add-on modules, allowing for fully-coupled and customized analyses. This dramatically reduces the need for writing user subroutines in order to customize equations, material properties, boundary conditions, or source terms.

3. Results and discussion
In this paper, we have studied the effects of RHF on toroidal field ripple using Comsol Multiphysics software. The RHF Coil with different values of $q = m/n$ modes ($n = 1$ and $m = 2, 3, 4, 5, 2&3$) was designed and simulated. Results are plotted in figure 2.

![Figure 2. Resonance helical perturbation Coil design as seen from the top of the tokamak. The narrow which wrapped the chamber for pictures b–f is RHF coil; a) without RHF coil; b) RHF coil with $q = 2$; c) RHF coil with $q = 3$; d) RHF coil with $q = 4$; e) RHF with $q = 5$; f) RHF with $q = 2&3$.](image-url)
Results of calculation of the ripple for three ratios of the RHF coil current/toroidal coil current 0.1, 1, 10 respectively are shown in figures 3, 4, and 5.

Figure 3 shows the intensity of magnetic field without and with RHF at different modes for the RHF coil current / toroidal coil current = 0.1.

Figure 3. The color plot with magnetic field arrows from above tokamak: a) without RHF; b) RHF with $q = 2$; c) RHF with $q = 3$; d) RHF with $q = 4$; e) RHF with $q = 5$; f) RHF with $q = 2\&3$. The arrows and the color intensity show the direction and amplitude of magnetic field entire the tokamak chamber.

Figure 4. The color plot with magnetic field arrows from above tokamak a)without RHF b) RHF with $q=2$ c) RHF with $q=3$ d) RHF with $q=4$ e) RHF with $q=5$ f) RHF with $q=2\&3$. The arrows and the color intensity shows the direction and amplitude of magnetic field entire the tokamak chamber.
Figure 4 shows the intensity of magnetic field without and with RHF at different q modes for the RHF coil current / toroidal coil current = 1.

Figure 5 shows the intensity of magnetic field without and with RHF at different q modes for the RHF coil current / toroidal coil current = 10.

**Figure 5.** The color plot with magnetic field arrows from above tokamak a) without RHF; b) RHF with \( q = 2 \); c) RHF with \( q = 3 \); d) RHF with \( q = 4 \); e) RHF with \( q = 5 \); f) RHF with \( q = 2 \& 3 \). The arrows and the color intensity shows the direction and amplitude of magnetic field entire the tokamak chamber.

The Magnetic field intensity plots in figures 6, 7, 8 show that RHF has affection on toroidal field ripple. As it is clear, the RHF effect increases by increasing current in the RHF coil (RHF coil current / toroidal coil current ratio) as expected. The modulate magnetic field without RHF is because of toroidal magnetic ripple itself. As mentioned before, the magnetic field is stronger within the plane of the toroidal coils than between the coils. This difference of intensity makes magnetic field modulation. This modulation is added to the plot for a better understanding of RHF effects in different q modes.

**Figure 6.** The toroidal ripple for different q modes at (RHF coil current / toroidal coil current = 0.1)
Figure 7. The toroidal ripple for different q modes at (RHF coil current / toroidal coil current = 1).

Figure 8. The toroidal ripple for different q modes at (RHF coil current / toroidal coil current = 10).

| $I_{RHF}$ | $I_{Toroidal}$ | Without RHF | Mode2 | Mode3 | Mode4 | Mode5 | Mode2&3 |
|-----------|----------------|-------------|-------|-------|-------|-------|---------|
| 0/1       | 1.53           | 1.53        | 1.52  | 1.52  | 1.51  | 1.53  |
| 1         | 1.53           | 1.51        | 1.54  | 1.5   | 1.53  | 1.49  |
| 10        | 1.53           | 1.3         | 1.68  | 1.27  | 1.76  | 1.49  |
4. Conclusion

The numerical results which obtained from the simulations show that for \( q \) modes of even numbers, the toroidal field ripple is reduced, and for \( q \) modes of odd numbers, the toroidal field ripple is increased. Also, we have low discrepancy for mode \( q = 2 \& 3 \) (Table 1). However, the modulation of magnetic field lines in high current ratio has high amplitudes which mess up the magnetic field distribution (figure 8).

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