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The effect of toroidal field on the rotating magnetic field current drive in rotamak plasmas*

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A rotamak is one kind of compact spherically shaped magnetic-confinement device. In a rotamak the plasma current is driven by means of rotating magnetic field (RMF). The driven current can reverse the original equilibrium field and generate a field-reversed-configuration. In a conventional rotamak, a toroidal field (TF) is not necessary for the RMF to drive plasma current, but it was found that the present of an additional TF can influence the RMF current drive. In this paper the effect of TF on the RMF current drive in a rotamak are investigated in some detail. The experimental results show that addition of TF increases the RMF driven current greatly and enhances the RMF penetration dramatically. Without TF, the RMF can only penetrate into plasma in the edge region. When a TF is added, the RMF can reach almost the whole plasma region. This is an optimal strength of toroidal magnetic field for getting maximum plasma current when $B_{\rm v}$ and radio frequency generator power are fixed. Besides driving current, the RMF generates high harmonic fields in rotamak plasma. The effect of TF on the harmonic field spectra are also reported.

Keywords: rotamak, rotating magnetic field, toroidal field
PACC: 5200, 5220, 5225

1. Introduction

A rotamak is one kind of unique device that can realize field-reversed-configuration (FRC) through current drive by rotating magnetic field (RMF).[1] In a rotamak, the electrons are trapped and rotated synchronously with external applied RMF, the plasma current is produced while ions are regarded as stationary background. The principle of current drive by RMF in a rotamak has been extensively studied.[2−7] For driving current effectively, RMF is chosen to satisfy $\omega_{\rm ci} \ll \omega \ll \omega_{\rm ce}$ and $\omega_{\rm ce}/\gamma_{\rm ei} > a/\delta$, where $\omega_{\rm ci}$ and $\omega_{\rm ce}$ are ion and electron cyclotron frequency around the RMF B_ω respectively, $\gamma_{\rm ei}$ is the electron–ion collision frequency and a is the plasma radius, $\delta = (2\eta_{/}\mu_0\omega)^{1/2}$ is the classical penetration depth at the RMF frequency ω. Except its compact configuration, the current in rotamak is driven and maintained by RMF which is usually powered by radio frequency (RF) generators, it has another advantage of the possibility of operation in continuous mode. Owing to its unique feature, the rotamak has stimulated more and more interest in fusion plasma recently.

The current drive in rotamak and realizing FRC have been studied in experiments and theories since the early 1980s and a lot of progress has been made.[2−13] It is reported recently that if an additional toroidal field (TF) is added, the current drive is improved and the rotamak can run as a low aspect ratio spherical tokamak (ST).[14] Up to now, what causes the TF to improve current drive is unknown, there are only several ambiguous theoretical papers.[15,16] So further study about the influence of TF on the RMF current drive is necessary for understanding the reason of TF improving the RMF current drive. In this paper the RMF current drive with and without TF and the change of plasma behaviour are presented. Our experimental results show that the TF will improve RMF penetration and increase the plasma current greatly. TF also affects the harmonics fields stimulated by RMF. This paper is organized as follows. In Section 2 a brief introduction of the experimental device is given. In Section 3 the experimental results are presented. In the end there is a summary in Section 4.

2. Experimental setup

Figure 1 is the structure of the rotamak device. The rotamak chamber is a spherical vessel made from

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Pyrex with 50 cm diameter. The chamber is pumped by a 500 l/S turbo pump and the background vacuum is around 1.333×10^{-4} Pa. The RMF is produced by passing RF currents, from two 400 kW/500 kHz RF generators, dephased by 90°, through two pairs of orthogonal Helmholtz coils located on the outside of the chamber. The plasma current generated by RMF is kept in equilibrium by vertical magnetic field which is produced by two vertical field coils with 83 cm diameter. The coils are connected in parallel and powered by a 20 kW DC power supply. The coils can produce a field up to 130 G in the vessel centre. In addition, by using an axial current (I_z in Fig.1), a TF can be added to the rotamak plasma. The system that produces TF consists of a set of six wires fed through the central axial stainless steel pipe with an external diameter of 4 cm. The steady toroidal magnetic field B_ϕ is produced by discharging a capacitor bank (maximum 152 kJ) through the wires. The discharge current threads the central axis six times, resulting in a total I_z current up to 18 kA, which can produce a TF $B_\phi = 288$ G at the half-radius of the chamber, $r = 12.5$ cm.

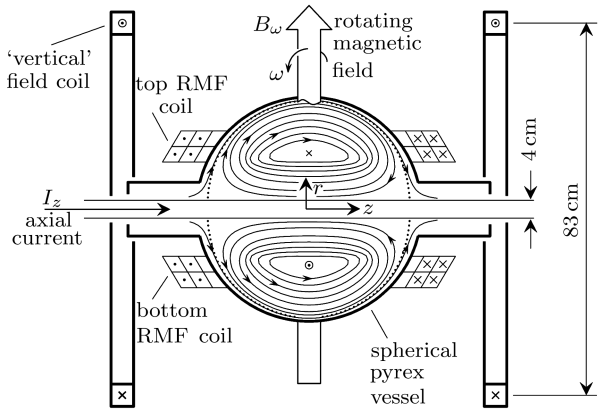


Fig.1. Schematic diagram of rotamak.

A Rogowski coil through the central tube and around a poloidal cross section is used to measure the driven plasma current. Align with the meridian plane of the chamber, there are 15 diagnostic ports with 6 mm inner diameter, which allow inserting probe into chamber for measurement. Miniature magnetic pickup coils and hall probe, which retractable through quartz guide tube sealed in diagnostic port, are used to measure the oscillating magnetic field and the steady magnetic field in the plasma respectively. A double floating Langmuir probe is used to measure the electron density and temperature of plasmas. Based on the shot to shot repeatable discharges the radial profiles of the parameters are got.

It is important to match the generator and plasma load for coupling the energy from the RF generators to plasma as large as possible. For this purpose there is a matching and tuning circuit in each RMF coil pair and there are RF voltage meters and current sensors for measurement. In air-core transformer model,[17] each matching and tuning circuit can be simplified as Fig.2. Here L_c and R_c are inductance and resistance of RMF coils, ΔL is the change of inductance caused by plasma, R_p is the reflection resistance of plasma. V_{in} and I_{in}, V_{ld} and I_{ld} are the voltage meters and current sensors for monitoring the voltage and current input from generator and load on the RMF coils respectively. During experiments, by adjusting the value of matching inductance L_m, the capacitance of matching and tuning capacitors C_M, C_T, let the phase between the V_{in} and I_{in}, V_{LD} and I_{LD} become zero and then the maximum plasma current will be produced.

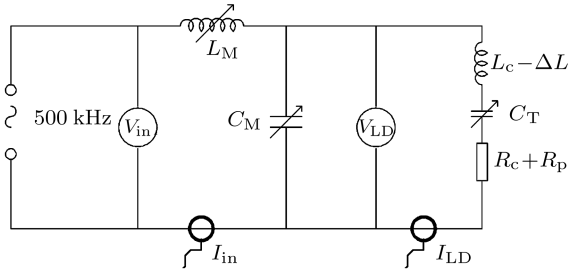


Fig.2. The matching and tuning circuit.

During experiments, hydrogen continuously flows through the chamber. The filling pressure is controlled by a mass flow controller. The discharges are very stable and reproducible from shot to shot when conditions keep same.

3. Experimental results

3.1. Effect of TF on the RMF current drive

Figure 3 is a typical time evolution waveform of plasma currents and the axial magnetic field B_z in $r = 3.5$ cm in the cases with and without TF. Table 1 is the typical parameters of the two cases. For comparison, in both cases the power from RF generators P_{rf} and the gas filling pressure P_f are kept unchanged.

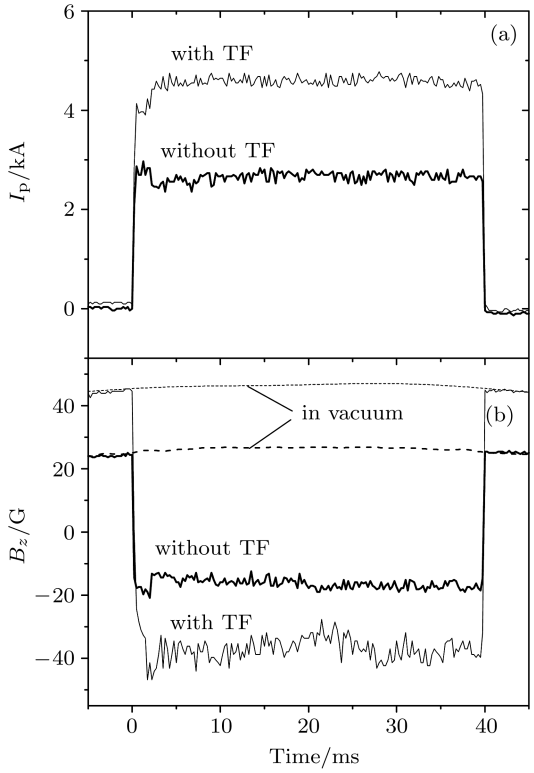


Fig.3. The typical time evolution of plasma currents and the axial magnetic field B_z in $r = 3.5$ cm in the cases with and without TF.

Table 1. The typical parameter for shot of Fig.3.

	without TF	with TF
P_f/Pa	0.18	0.18
P_{rf}/kW	2×180	2×180
B_v/G	25	45
I_z/kA	0	9.0
I_p/kA	2.7	4.7
n_e/cm^{-3}	1.4×10^{12}	1.2×10^{12}
T_e/eV	22	30
I_{RMF}/A	88	51
R_p/Ω	26	87

The power from each RF generator is 180 kW and the gas filling pressure is 0.18 Pa. In the case without TF, the biased vacuum vertical field B_v is 25 GS at the centre of chamber. In the case with TF, a 9 kA axial current is added and the vertical field B_v needs to be increased to 45 GS for keeping the increasing plasma current in equilibrium. Figure 3 shows clearly that the addition of TF dramatically increases the RMF driven current, the plasma current increased from 2.7 KA without TF to 4.7 KA with TF, almost doubled. It also indicates that after launching the RMF, the magnetic field produced by RMF driven plasma current reverses the vacuum vertical field (marked by dash line). In the case without TF, this is a compact FRC[1,10] and in the case with TF a spherical tokamak (ST) configuration is generated, as reported in Refs.[1,14].

Besides improving the total RMF driving current, the addition of the TF can also change the plasma current density profile. The plasma current density can be deduced from $J_\theta = \frac{1}{\mu_0}\left(\frac{\partial B_r}{\partial z} - \frac{\partial B_z}{\partial r}\right)$. In experiments only the magnetic fields along the $z = 0$ central channel have been scanned, and the first term in J_θ expression is omitted, which implies that the infinite cylindrical configuration approximation is used, which is not quite accurate in our case. By comparing the profiles of our J_θ with that obtained in the previous rotamak operation,[14] where the complete (r, z)-scan of the magnetic field was performed, we find that neglecting the first term in J_θ results in underestimation of the J_θ value, around 20%. But current density profiles are not much different. So $J_\theta = -\frac{1}{\mu_0}\frac{\partial B_z}{\partial r}$ is used to characterize the current density profile in the cases with and without TF.

Figure 4 is the profile of B_z in the $z = 0$ central channel at the middle of the shots in the cases with and without TF in the same discharge condition as Fig.3. Figure 5 is the current density profiles calculated by using $J_\theta = -\frac{1}{\mu_0}\frac{\partial B_z}{\partial r}$ from Fig.4. Before calculation, the experimental measurement B_z data

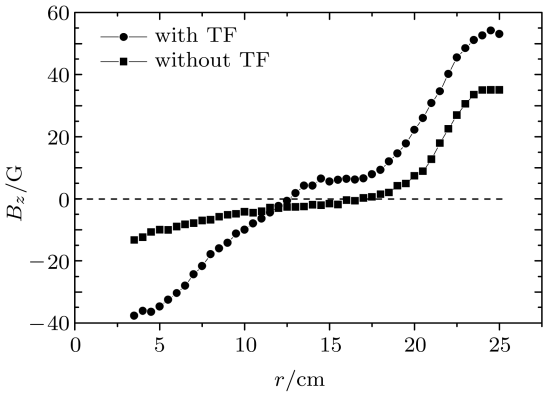


Fig.4. The profile of B_z in $z = 0$ channel with and without TF.

are fitted by a proper polynomial curve. From Fig.5, it is found that the current density in the rotamak has a distinct character that consists of two rings. The profiles are hollow with two peaks located on both sides of the magnetic axis, forming the inner and outer rings. The peak value of the outer ring is larger than that of the inner ring. In the TF case, however, the peak current density of the inner ring becomes larger

than that in the case without TF, roughly three times larger. And at the same time the peaks of two rings are closer to the magnetic axis in ST.

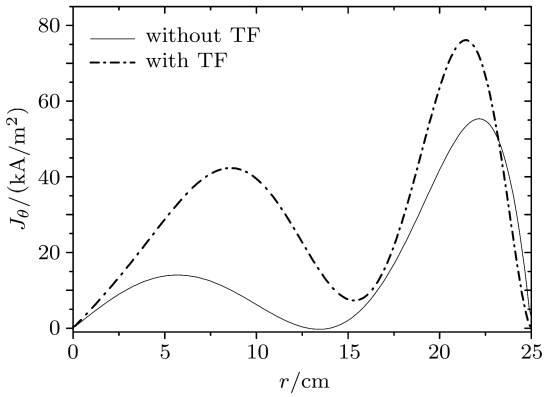


Fig.5. The current density profile with and without TF.

The RMF current drive in the rotamak is strongly dependent on the biased vertical magnetic field. Figure 6 shows the relation of the plasma current with the vertical magnetic field B_v in the cases with and without TF when the RF power and gas filling pressure are fixed at the same values as the Fig.3. It is indicated that in both cases, the plasma current I_p increases almost linearly with B_v, but in the discharges with TF the I_p grows faster with B_v than in the case absent from TF. Using the linear fit to the data, we obtain that the slopes are 86 A/G and 118 A/G in the cases with and without TF respectively. It is worth mentioned that the Solov'ev equilibrium[18] predicts this ratio to be $\dfrac{I_\mathrm{p}}{B_\mathrm{v}} = \dfrac{5a}{\mu_0} = 99\,\mathrm{A/G}$, where a is the radius of plasmas. The experimental results are very close to the predicted results. This implies that the rotamak plasma current should satisfy equilibrium magnetic configuration, and the rotamak has the common properties as other magnetic confinement devices.

Another important result from Fig.6 is that the addition of TF not always enhances the RMF current drive. Actually in low vertical field the presence of TF will decrease the plasma current. It was reported that in cases without TF, for a certain RF power, the current can not increase with B_v infinitely, there is a critical B_v (28 G as shown in Fig.6) that above this value current termination will occur.[17,19] From Fig.6, it seems that below this critical B_v, the presence of the TF is disadvantageous for the RMF-driven plasma current. When the vertical field exceeds the critical value, the addition of TF increases the RMF current. However, similar to the case without TF, there is a current termination point also in the case with TF ($B_\mathrm{v} \approx 48\,\mathrm{G}$ in the present case), when $B_\mathrm{v} > 48\,\mathrm{G}$ a stable plasma current can not be achieved. So the presence of TF postpones the occurrence of the current termination from low B_v region to high B_v value (from 28 G in the case without TF to 48 G in the case with TF).

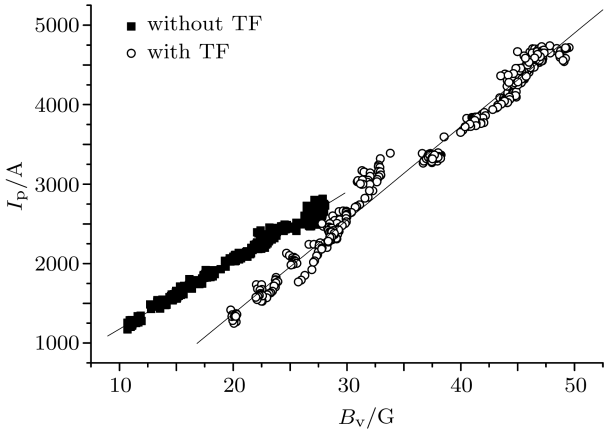


Fig.6. The dependence of plasma current I_P on the biased vertical field.

The I_p–B_v relation in the case with TF in Fig.6 is found with the condition that the axial current is fixed at 9 kA. In order to deep study the effect of the strength of TF on the RMF current drive in case with TF, we keep the other parameters unchanged; only varying the TF, i.e. the axial current I_z. The power from two RF generators is $P_\mathrm{rf} = 2 \times 180\,\mathrm{kW}$, the gas filling pressure is 0.18 Pa, as those in the previous case. The results are shown in Fig.7 for the two cases of the vertical fields 35 and 45 GS. It is shown that in a certain vertical field, RF power, and filling pressure, there is a

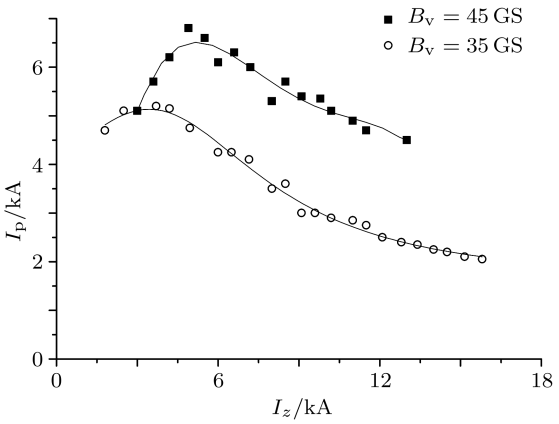


Fig.7. The relation of plasma current and the toroidal field current I_z.

range of the axial current values that the stable plasma can be obtained. For $B_{\rm v} = 45\,{\rm G}$, for example, when the axial current is smaller than 3 kA or larger than 18 kA, it is difficult to get or maintain stable plasma current. The second conclusion from Fig.7 is the existence of the optimal value of the axial current for the largest plasma current, and this optimum is different for each value of $B_{\rm v}$, for instance, 5 kA for $B_{\rm v} = 45\,{\rm GS}$.

3.2. Effect of TF on harmonic fields oscillation and RMF penetration

It is important to know the extent that the RMF can penetrate into the plasma and the relation between the RMF penetration and the current drive in the rotamak. For studying the RMF penetration during the current drive in the rotamak plasma, the oscillating magnetic fields have been measured by pickup coils. And it is found that besides the fundamental fields, there are high order harmonics generated by RMF and their frequency spectra are different in the shots with and without TF. Figure 8 gives the spectra of time derivative signals of $\dot{\tilde{B}}_r$, $\dot{\tilde{B}}_\theta$ in the same condition as that in Fig.6. It indicates clearly that significant harmonics are generated in the rotamak plasma. In the case without TF, the harmonics are dominated by 1, 3, 5, 7 *et al* odd orders, the amplitude of even orders are small in comparison with the odd ones. For instance the amplitude of third order is larger than second order. From Figs.8(c) and 8(d) when TF is added, amplitudes of both even and odd orders become large. Opposite to the case without TF, the amplitude of the second order now is larger than the third ones. The ratio between the maximum magnetic amplitude of harmonics and the fundamental one is $B_{3\omega}/B_{1\omega} \sim 26\%$ in the case without TF, and $B_{r2\omega}/B_{r1\omega} \sim 45\%$ in the case with TF. The reason for generating the harmonics is the Hall term $\boldsymbol{J} \times \boldsymbol{B}$ which was reported elsewhere.[20]

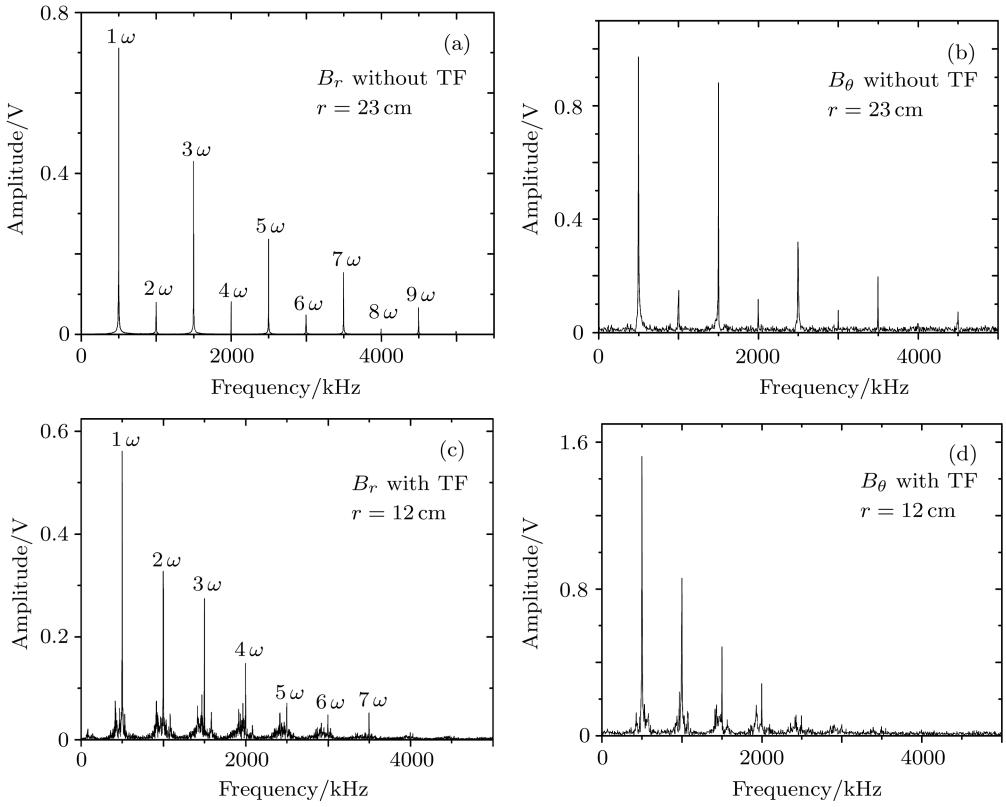


Fig.8. Frequency spectra of $\dot{\tilde{B}}_{\rm r}$ and $\dot{\tilde{B}}_\theta$ without TF (a,b) and with TF (c,d).

Besides the change of the harmonic field frequency spectra, the addition of TF improves the RMF penetration greatly. Figure 9 is the radial profile of $1\,\omega$ fundamental field. For comparison, the RMF magnetic profile in vacuum (without plasma) is also plotted. It is found that the penetration of RMF is very different

in the cases with and without TF. In the case absent from TF the RMF can only penetrate into plasma in the edge region, in the region from edge to 15 cm of the chamber. When TF is applied, penetration of RMF is improved dramatically, it now can be penetrated almost whole volume of the plasmas and the maximum field positions are shifted to inner region. Owing to the penetration of RMF and the generation of J_z in plasma, the amplitude of B_θ in both cases can be larger than its vacuum value.[6,13]

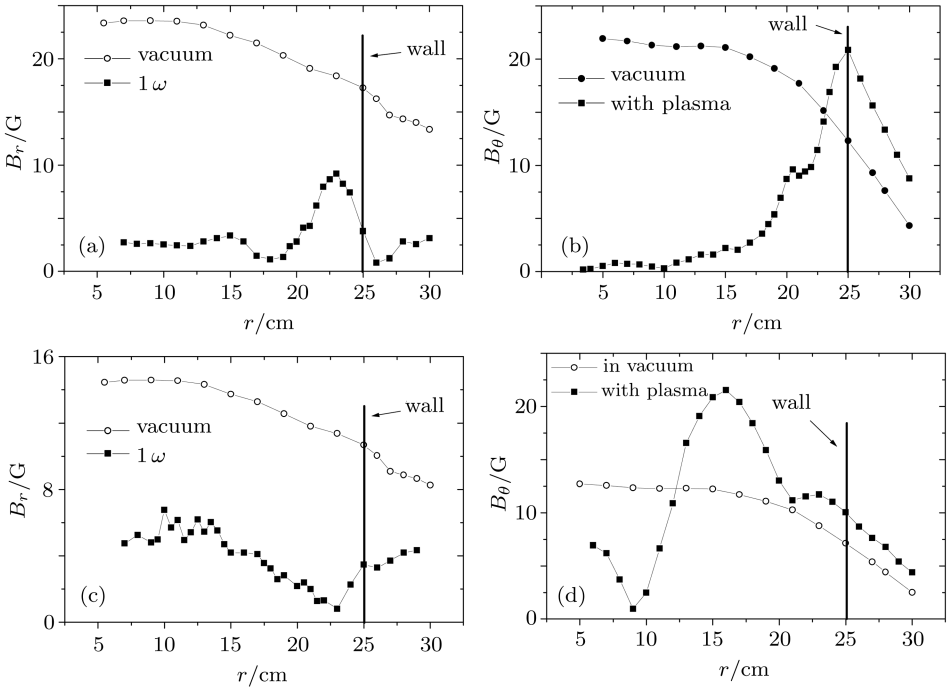


Fig.9. Radial profile of B_r and B_θ without TF (a,b) and with TF (c,d).

Another evidence of improving RMF penetration by TF is the change of plasma reflection resistance. In these shots, the powers coupled into the load are almost the same, which are monitored by $V_\mathrm{ld} \times I_\mathrm{ld}$ in Fig.2. But the RF current through RMF coils decreases from 88A in the case without TF to 51A with TF. The plasma reflection resistance calculated from $R_\mathrm{p} = V_\mathrm{ld}/I_\mathrm{ld} - R_\mathrm{c}(R_\mathrm{c} = 4\,\Omega)$ increases from 26 Ω to 87 Ω. According to the air-core transformer model, the plasma reflection resistance can be written as[17]

$$R_\mathrm{p} = \frac{k^2 L_\mathrm{c} r_\mathrm{p}}{L_\mathrm{s}}$$

where k is the coupling coefficient between the RMF coils and plasma current through the mutual inductance $M = k\sqrt{L_\mathrm{c}L_\mathrm{s}}$, L_s is the inductance of plasma, L_c is the inductance of RMF coil in Fig.2, r_p is the plasma resistance. In the discharges with and without TF, the L_s is not much different, which is evidenced by the little change of the matching and tuning capacitor when matching the discharges. And the r_p will be smaller in the case with TF owing to higher plasma temperature (reported in Section 3.3). The increase of R_p is owing to the increase of the coupling constant k. It implies that the penetration of RMF is improved in the cases with TF.

3.3. Effect of TF on plasma density and temperature

The electron density and temperature in the discharges with and without TF are measured by double floating Langmuir probe. Figure 10 is the electron density and the temperature profiles in the $z = 0$ cm central channel in the same discharge conditions in Fig.3. It is shown that the addition of TF increases the electron temperature. The electron temperature increases from 20 eV in the shots without TF to 35 eV when the TF is added. In both cases, the electron temperature is almost uniform in the whole plasma region. But the maximum electron density in the case with TF is a little lower than that in the case without TF.

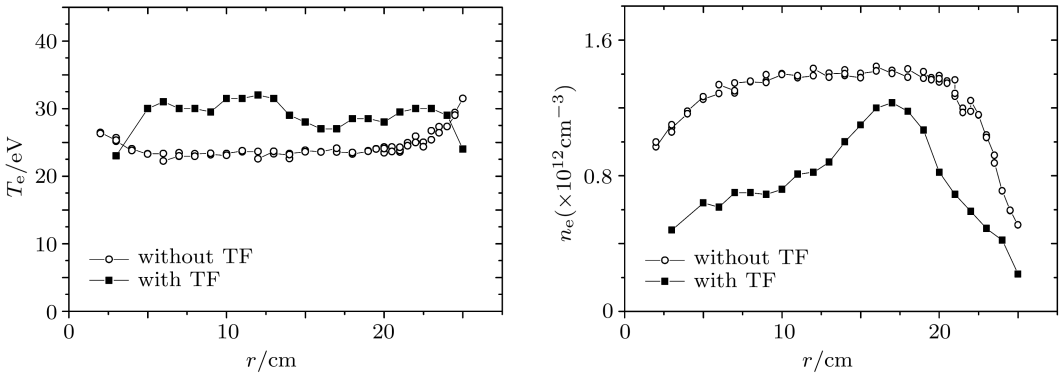


Fig.10. The electron temperature and density in cases with and without TF.

4. Conclusions and discussions

The effect of toroidal magnetic field on the RMF current drive in a rotamak is studied. The experimental results show that addition of an external TF increases the RMF driven current greatly and enhances the RMF penetration dramatically. Without TF, the RMF can only penetrate into plasma in the edge region. When a TF is added, the RMF can reach almost the whole plasma region. This is an optimal strength of toroidal magnetic field for getting maximum plasma current when B_v and RF generator power are fixed. The electron temperature increases also in the discharge with TF. The driven current is linearly proportional to the vertical field in the both cases with and without TF. But the addition of the TF postpones the 'current termination' which occurs in the small vertical field B_v in the discharges with TF and stable discharge can be obtained in higher B_v with larger current. Besides driving current, the RMF can generate high harmonic fields in a rotamak plasma. In the case without TF the harmonics are dominated by odd orders. The presence of TF enhances the even harmonics greatly.

From Fig.9, it is seen that the RMF magnitude is almost zero in the inner region of the plasma in the case without TF. So the inner current ring appearing in Fig.5 in this case is not driven by RMF. There should be other reasons to produce this current. One possible mechanism for generating the inner current ring is the convective flux of the particles in the rotamak plasma. As reported in Ref.[7] there is a poloidal swirling flow in RMF driven plasma, which provides a torque for the inner current ring, through the Hall term $u_r B_z$, where u_r is the radial component of the swirling flow.

The value of the radial flow speed u_r can be estimated from $n_\mathrm{e}u_r = -D_\perp \dfrac{\partial n_\mathrm{e}}{\partial r} \approx -D_\perp \dfrac{n_{\mathrm{e}0}}{a/2}$, so that $u_r \approx -\dfrac{2D_\perp}{a}$. Using the formula for diffusion rate, $D_\perp = n_\mathrm{e}\eta_\perp kT_\mathrm{e}/B^2$ we get $J_\theta = \dfrac{u_r B_z}{\eta_\perp} \approx -\dfrac{2D_\perp}{a\eta_\perp}B_Z \approx -\left(\dfrac{2}{a}\right)\dfrac{n_\mathrm{e}kT_\mathrm{e}}{B_z} \approx -18\,\mathrm{kA/m^{-2}}$, which is close to the experimental value.

The reason for improvement of the RMF driven current by TF is not clear as yet. Bertram[15] and Watterson[16] investigated the effect of the TF on RMF driven current respectively in the cylindrical configuration and obtained ambiguous results. Bertram's numerical and analytical results indicate that, for a plasma of low resistivity, imposing a strong TF reduces the amount of current that can be driven, for a resistive plasma the effect is complicated. When the magnetic field strength is near that of RMF, $B_\mathrm{tor} \sim B_\omega$, the present of TF would increase the driven current a little. When the TF increases, the driven current is reduced. Whereas from Watterson's analytical results, the addition of the TF is always harmful to the penetration of RMF and reduces the current drive, no matter the plasma resistivity is low or high. As shown in our experiments, however, the TF always increases the RMF driven current, only if the biased vertical value is larger than that of the termination value. One reason that the present theories can not explain the experimental phenomena properly may be that the theoretical analysis is conducted in cylindrical configuration, and the real shape of the rotamak is a spherical torus. Another reason for the disagreement between the theory and experiments maybe that, from the increase of the electron temperature in

the case with TF, the addition of TF may improve the plasma confinement. So in the future theoretical study, the analysis should be conducted in spherical configuration, the real shape of the rotamak device and the energy transportation process should be included also.

References

[1] Jones I R 1999 *Phys. Plasmas* **6** 1950

[2] Hugrass W N, Jones I R, McKenna K F and Philips M G R 1980 *Phys. Rev. Lett.* **44** 1676

[3] Jones I R and Hugrass W N 1981 *J. Plasma Physics* **26** 441

[4] Hugrass W N 1982 *J. Plasma Physics* **28** 369

[5] Hugrass W N and Grimm R C 1981 *J. Plasma Physics* **26** 455

[6] Hoffman A L 1998 *Phys. Plasmas* **5** 979

[7] Milroy R D 1999 *Phys. Plasmas* **6** 2771

[8] Milroy R D 2000 *Phys. Plasmas* **7** 4135

[9] Hoffman A L 2000 *Nucl. Fusion* **40** 1523

[10] Euripides P, Jones I R and Deng C B 1997 *Nucl. Fusion* **37** 1505

[11] Slough J T and Miller K E 2000 *Phys. Rev. Lett.* **85** 1444

[12] Slough J T and Miller K E 2000 *Phys. Plasmas* **7** 1945

[13] Guo H Y, Hoffman A L, Brooks R D, Peter A M, Pietrzyk Z A, Tobin S J and Votroubek G R 2002 *Phys. Plasmas* **9** 185

[14] Jones I R, Deng C B, El-Fayoumi I M and Euripides P 1998 *Phys. Rev. Lett.* **81** 2072

[15] Bertram W K 1987 *J. Plasma Physics* **37** 423

[16] Watterson P A 1988 *J. Plasma Physics* **40** 109

[17] Euripides P 1998 *Experimental Investigation of Power Transfer in the 50 Liter Rotamak,* Ph.D thesis, Flinders University of South Australia

[18] Solov'ev L S 1976 *Reviews of Plasma Physics* vol **6** (New York: Consultants Bureau) p239

[19] Donaldson N, Euripides P, Jones I R and Xu S 1995 *Plasma Phys. Control. Fusion* **37** 209

[20] Zhong F C, Petrov Y and Huang T S 2004 *Phys. Plasmas* **11** L1