Plasma poloidal rotation generated by RF cyclotron heating in tokamaks

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1, Introduction

The improved confinement in magnetically confined tokamak plasmas is an attractive topic. It has been discovered that the improved confinement can be conducted by generating sheared $\vec{E} \times \vec{B}$ flow[1]. There are a few ways to produce the $\vec{E} \times \vec{B}$ flow, one of which is to rotate plasma poloidally.

In this paper, we introduce a mechanism of production of plasma poloidal rotation by using RF waves in range of either ion cyclotron frequency or electron cyclotron frequency. The physics process is described as follows[2-4]: During RF cyclotron heating in tokamak plasmas, RF waves make ions accumulate poloidally because RF waves preferentially drive resonant particles diffusing in the perpendicular direction(corresponding to the magnetic field). This kind of ion accumulation can overwhelm the damping of the magnetic pumping and destabilize the plasma poloidal rotation.

2, Physics description and basic equations

RF cyclotron heating in tokamak plasmas includes both electron cyclotron resonant heating (ECRH) and ion cyclotron resonant heating (ICRH). In these two kinds of heating approaches, the manners of making ion poloidal accumulation are different[4]. During ICRH, RF wave directly induces resonant ion accumulation poloidally because of the resonant particle localization[7] in the collisionless region. During ECRH, RF wave produces a poloidal electric field by either the resonant localization or the inhomogeneous power deposition[8], dependent on the collision strength. Under the action of this electric field, ions would accumulate poloidally. If the rate of ion accumulation is big enough, a kind of plasma poloidal rotation can be destabilized. The production of plasma poloidal rotation changes the local $\vec{E} \times \vec{B}$ flow and may trigger the improved confinement mode.

Assuming the induced ion profile is $\tilde{n} = \hat{n} F(\theta)$, where $\hat{n}$ is the amplitude of ion poloidal inhomogeneity and $F(\theta)$ is the profile of ion poloidal distribution. Then the ion accumulation rate can be expressed as $\tilde{n} / \tau_0$, where τ_0 is the characteristic time of formation of the poloidal ion density profile. Based on the fluid equations, we can evaluate the destabilization condition as[4,5]

$$\frac{\hat{n}}{n} \geq \frac{\eta_0 \tau_0}{nm} \frac{< (\vec{b} \cdot \nabla B)^2 >}{\left| < \Delta_b F(\theta) > \right| < B^2 >} \tag{1}$$

,

where m and n are respectively the ion mass and density. The symbol $<\ >$ denotes the flux average operation. $\vec{b} = \vec{B}/|B|$, B is the magnetic field and $\Delta_b = (B^2 - < B^2 >)/ < B^2 >$. The parallel viscous coefficient η_0 is[6]:

$$\eta_0 = \varepsilon^{-3/2} qRnmv_{th} \frac{v_i^*}{(1 + \varepsilon^{-3/2} v_i^*)(1 + v_i^*)} , \qquad (2)$$

where $v_i^* = v_i / v_{ti}$, $v_i = \tau_i^{-1}$ is the ion collision frequency and $v_{ti} = v_{thi} / qR$ is the ion transit frequency and v_{thi} is the ion thermal velocity.

The poloidally inhomogeneous ion distribution during rf cyclotron heating can be studied by the drift kinetic equation:

$$\frac{\partial f_0}{\partial t} + v_{//}\vec{b} \cdot \nabla f_1 + e\vec{E} \cdot \vec{b} v_{//} \frac{\partial f_0}{\partial W} = C(f) + Q(f) , \qquad (3)$$

where the standard notation is used. The poloidal ion density perturbation is given by

$$\tilde{n} = \int f_1 d^3 v = \int e\phi \frac{\partial f_0}{\partial W} d^3 v .$$

3. Poloidal rotation criteria

In the different situations, there are different mechanisms responsible for the poloidal accumulation of ions during rf cyclotron heating as stated before. For simplicity, we express ion poloidal density distribution as a cosine. In the following we give a summary of the destabilization criteria of the poloidal rotation in the different cases.

a) ICRH minority heating

During ICRH minority heating the resonant ions accumulate poloidally in the action of rf waves because of the resonant particle localization. The characteristic time of energetic ions to reach the steady state is the order of the electron slowing down time. Then from Eq.(1), we obtain the criterion to destabilize the poloidal rotation as[3]

$$\frac{\hat{n}}{n} = \frac{42.5}{2\sqrt{\varepsilon}} \frac{z_i^2 n_i}{n_e} (\frac{m_i}{m_p})^{0.5} (\frac{T_e}{T_i})^{1.5} . \qquad (4)$$

By employing a numerical code of solving the bounce-averaged Fokker-Planck equation, we have shown[3] that in the present power level, it is possible to produce poloidal rotation of minority species of ions.

b) ECRH core heating

In core region, plasma is relatively collisionless. The poloidal electric field is produced by the resonance electron localization. Ions should be redistributed poloidally according to the poloidal electric field. It is difficulty to analytically determine the poloidal electric field for a realistic tokamak plasma. For the sake of magnitude instructions, we employed the result of Ref.[7], which evolves in some approximations. In this case, the rf power criterion to

destabilize the rotation is obtained as[4]

$$P = \frac{0.94\sqrt{\pi}}{z_{eff}\varepsilon^{3/2}}\frac{nT}{\tau_i}.$$
(5)

For the usual tokamak parameters, this power density is attainable.

c) ECRH edge heating

In edge plasma where the collision is stronger, the mechanism for production of the poloidal electric field is different from that in core heating case. The inhomogeneous rf power deposition can produce the poloidal electron accumulation. The rf power criterion of rotation production is[4]

$$P = \frac{0.96\pi}{q^2 R^2}\frac{nT^2}{A_n m}\frac{v_{te}^2}{v_e^2}\tau_i,$$
(6)

where $v_{te} = v_{the}/qR$, v_e is the electron collision frequency. A_n is the poloidal inhomogeneous factor of rf power deposition for the n-th harmonic heating and $A_2 > A_1$[8].

4, Improved confinement

In the operation of improved confinement, there are many mechanisms to contribute the production of sheared flow. In the different conditions, the different mechanism may play a dominant role. Therefore we can observe many kinds of improved confinement modes with different appearances. If we think that the poloidal rotation produced by the mechanism introduced here can trigger the improved confinement, then this kind of improved confinement have some characters predicted by our analysis. For example, in collision region for a tokamak with parameters: q=7, R=2m, T=T_i=T_e=50ev, n=1×10^{19}m^{-3} during the second harmonic ECRH, $A_2 \approx 0.1$, then the power criterion can be obtained from Eq.(6) as P_c=2×10^{4}W/m^3. This value of rf power density has been attained for many present tokamaks. Also from Eq.(6), the power criterion can be scaled as $P \propto T^{7.5}/A_n n^2$, which predicts the following characters:

a) The rf power criterion is dependent on the heating manner. During the second harmonic heating a little less power is needed to trigger the improved confinement than that in the fundamental heating.

b) In the same absorbed power density, the closer to the edge, which means lower temperature, the resonant layer is, the easier the improved confinement is triggered.

c) The power criterion is very sensitive to the local temperature, which is related the radial position. Therefore the power criterion is very sensitive to the resonant position when the resonant position is shifted along the minor radius of tokamak plasmas.

d) The power criterion decreases with the density increasing.

e) The resultant ion density must be higher in the lower field side, which means there are

differences for the resonant layers with the same radial position but different poloidal position.

It is difficulty to find experiments to make a quantitative comparison because the experiments performed before have not given the details we need. But we can pick some experiments to make an interesting contrast. Taking one experiment[9] performed in JFT-2M as an example, which shows that H-mode can be triggered by edge ECRH. ECRH was applied with the second harmonic launched from the lower field side. The H-mode transition was observed by a small rf power deposited at the very edge of the plasma. When scanning the resonant position from r/a=0.32 to 1.1, it is found that only in the edge region(r/a~0.58-0.87) the rf power threshold sharply decreases with the resonant position being shifted outward. It is also found that by raising the plasma density, the H-mode transition was observed at a lower power. If we presume that the H-mode transition mentioned above is triggered by the generation of poloidal rotation. The some characters observed in this JFT-2M experiment are the same as the predictions of our model. Therefore the mechanism introduced here may be a potential candidate to practically generate the plasma poloidal rotation in tokamaks.

5, Conclusions

We have introduced a mechanism of generating plasma poloidal rotation by using rf cyclotron heating within an attainable rf power in tokamaks. Based on the production mechanism of the poloidal rotation given above, we present a L/H transition model: the plasma poloidal rotation can be destabilized by the ion poloidal accumulation, which is generated by rf waves during rf cyclotron heating. The improved confinement mode during RF cyclotron heating may be triggered by the plasma poloidal rotation mentioned above. According to the predictions of our model, we make a comparison with an experiment performed before, which shows some similarities.

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