APPROACH TO HIGH STABILITY BETA LIMIT AND ITS CONTROL BY FAST WAVE CURRENT DRIVE IN REVERSED FIELD PINCH PLASMA

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Abstract

Before the generation of steady state, dynamo-free RFP configuration by rf current driving scheme, it is necessary to find an optimum configuration into high stability beta limit against m=1 resonant resistive MHD modes and reducing nonlinearly turbulent level with less rf power. As first step to the optimization study, we are interested in partially relaxed state model (PRSM) RFP configuration, which is considerd to be closer to a relaxed state at finite beta since it has force-free fields for poloidal direction with a relatively shorter characteristic length of relaxation and a relatively higher stability beta limit to m=1 resonant ideal MHD modes. The stability beta limit to m=1 resonant resistive MHD modes can be predicted to be relatively high among other RFP models and to be enhanced by the current density profile control using fast magnetosonic waves (FMW), which are accessible to high density region with strong absorption rate.

1. INTRODUCTION

This study is preliminary one for the generation of RFP configuration optimized into higher stability beta limit against m=1 resonant resistive MHD modes, weakly dependent on wall stabilization effect and being in steady-state free from magnetic field diffusion and turbulent relaxation. Furthermore, generally the m=1 resonant MHD modes triggering the turbulent relaxation occur over entire plasma region. From these viewpoints, fast magnetosonic waves (FMW, $f_{DC}<f<f_{LH}$, Low and High Frequency FMWs) are used as current driver since it is accessible to high density region with strong absorption rate due to transit time magnetic pumping and with a relatively high current driving efficiency, as reported by us in literature [1].

2. BENEFIT OF CURRENT PROFILE CONTROL BY FAST MAGNETOSONIC WAVE(FMW)

The benefit of FMW current drive is theoretically demonstrated by the significant reduction of the nonlinearly turbulent level associated with the relaxation process in modified Bessel function model (MBFM) RFPs (force-free current distribution $\lambda=1.6\pi\{(\cos\pi r+1)/2\}^{0.96}$, normalized magnetic helicity $aK/P\Phi^2=6.87$), where a minimum energy state is in an axisymmetric equilibrium linearly unstable to m=1 kink modes ($\tilde{v}_r=0.1\{1-\cos(2\pi r)\}$). With only 14% fraction of rf-driven current to total current, the turbulence level is reduced to be smaller by an order of magnetude than that without rf injection, which suggests a significant improvement of energy confinement time. Then, the rf-current driving efficiency is typically ~0.73A/W depending on the beta value of target plasma and wave parameter ($S=3\times10^3$, $n_{e0}=4.3\times10^{20}/m^3$, $B_0=4.2T$, $\beta_0=15\%$, $Z_{eff}=1$, $R/a=1.6$, $a=0.3m$, $I_\theta=10.1MA$,

I_z=1.8MA, and F/Θ=0.01/1.77, f=300MHz, $N_{//0}$(initial parallel refractive index)=1, P_0(wave power injected)=1.5MW).

Generally, the m=1 resonant MHD modes triggering the turbulent relaxation occur over entire plasma region, then FMWs are used as an useful current driver to stabilize these modes.

3. STABILITY CONDITIONS AND ITS CONTROL BY FMW CURRENT DRIVE

Next problem is to find the more stable configuration in which the nonlinearly turbulent level is reduced with the less wave power. Hence, we are interested in the stability conditions of m=1 resistive MHD modes and its high beta approach by FMW current drive in partially relaxed state model (PRSM)-RFP configuration [2], which is characterized by the force-free fields, $\nabla \times B=\lambda B$, only for poloidal direction, a plasma pressure gradient to satisfy Suydam criterion ($S_0<1$), $dp/dr= -S_0 r B_z (dq/dr)2/8\mu_0 q^2$ (q is safety factor), the stable on-axis m=1 resistive MHD (tearing) modes, and a relatively high stability beta limit of central beta $\beta(0)$~19% with $S_0 \leq 1$ and F/Θ=-1.4/2.1 against both m=1 ideal MHD (kink) and Suydam localized modes, where the λ profile is assumed to be uniform, F is the field reversal ratio B_z(at wall)/<B_z>, Θ is the pinch parameter B_θ(at wall)/<B_z>.

The stability conditions of m=1 resonant resistive MHD modes in PRSM-RFP equilibrium with and without FMW current drive are examined by solving numerically maximum eigenvalues as initial value problem on the base of a linearized, compressible three dimensional MHD equations including resistivity, viscosity, thermal conduction terms. Cylindrical plasma is bounded by perfectly conducting wall. The form of λ profile is assumed to be of nonuniform function $\mu_0 j_\theta/B_\theta$ ($\equiv\lambda$)= $\{1-(\psi/\psi_W)m_\lambda\}n_\lambda$, where ψ and ψ_W are poloidal flux at a flux surface and wall, respectively. The used typical plasma parameters are total toroidal current I_z=2MA, plasma radius a=0.3m, aspect ratio R/a=3.0, and effective charge number Z_{eff}=2.0. In the computation, the normalized viscosity ν is usually set equal to the normalized resistivity η. Both ν and η are assumed to be isotropic and constant in space and time. The growth rates normalized to τ_A, γ, of the m=1 modes with toroidal mode number n=1 ~ 40 are calculated in the range of Landquist number S($\equiv\tau_P/\tau_A$, τ_R is resistive diffusion time, τ_A is Alfven time)=3×10^3~1×10^4 and thermal conduction coefficient $\kappa=1\times10^{-4}$. In the case of the λ profile with m_λ=5, n_λ=2, S_0=0.8, F/Θ=-0.2/1.76, in which central beta $\beta(0)$=7.8%, averaged poloidal beta $\bar{\beta}_p$=16.1% and volume averaged beta $\bar{\beta}$=5.5%, the stability calculation shows the PRSM-RFP plasma to be stable. The stability conditions are examined through the current profile control by FMW current drive. The comparison of λ-, p-, and β-profiles between stable and unstable cases indicates that the observed instability is due to the presence of positive gradient in λ profile while p and beta values increase by rf current drive. The growth rate γ is the largest for the internal resonance toroidal mode number at the peak position of λ value. The profile of perturbed plasma pressure has one node coincident with the resonance, indicating the unstable modes to be tearing-like internal modes. This is confirmed also by the dependence of γ on Landquist number S; the smaller is S number, γ becomes the larger for large n (depending on λ profile), which are considered to be resistive kink (tearing-modes) or resistive interchange (g-modes) instabilities, but the smaller for small n modes, which are considered to be ideal kink instabilities. As expected, the growth rate scaling is $\gamma \propto S^{-3/5}$ for tearing-modes and $\gamma \propto S^{-1/3}$ for g-modes [3]. The observed S dependence of γ reveals to be tearing-modes rather than g-modes, although it is the stronger compared with $S^{-3/5}$ scaling for large n modes. But, to make it sure, it may need to carry the stability calculation in the range of $S<3\times10^3$, although the smaller S number makes the spacial resolution worse. The smaller n modes ($n \leq 5$) corresponding to internal resonance modes in central region are not observed because PRSM-RFP configuration has Taylor form there and the curvature of pitch function P, $\zeta(=(P/2)d^2P/dr^2|r\rightarrow0)=-1/2$, then satisfies on-axis m=1 tearing-mode stability criterion $-4/5<\zeta$ and on-axis ideal-mode stability criterion $\zeta<-4/9$, i.e. the pitch function must decrease sufficiently rapidly as one moves away from the axis [4]. This criterion of $\zeta>-1$ implies directly that the axial current must be peaked on axis for stability ($\zeta=-1$ is a flat axial current distribution). However, the lower beta plasma ($S_0=0.4$, $\beta_p=8.24\%$) is stable even in the presence of $d\lambda/dr>0$ region, indicating a contribution of beta value to instabilities in addition to the positive gradient in λ profile.

Next we try to enhance stability beta limit by FMW current drive. Adjusting wave power P_0 at a fixed parallel refractive index injected $N_{//0}$ makes λ profile flatter and beta value higher than those without rf injection. In addition, keeping the initial plasma beta value of $\bar{\beta}_p=16.1\%$ and fixing wave power, λ profile becomes flatter and beta value higher for a selected I_z/N plasma (N is line density) since rf current driving efficiency increases with increasing T_e/n_e.

4. COMPARISON OF STABILITY BETA LIMIT

Note that, when the resistive diffusion of the equilibrium configuration is neglected, only instabilities can be studied whose characteristic time-scale is shorter than τ_R, the resistive diffusion time. For comparison, in a RFP model describing both the parallel and perpendicular current density components, if viscosity is neglected, resistive interchange modes (g-modes) are always present when $S_0<1$ [5]. For this reason and also because of the limit to the analysis posed by the resistive diffusion of the equilibrium configurations, a stable configuration, in which the growth rates are less than S^{-1} ($S=\tau_R/\tau_A$, τ_A is Alfven time), is considered and a kind of stability beta limit is defined as maximum stable beta value. The defined stability beta limit is $\bar{\beta}$ (volume averaged beta)~8.0% (Θ~1.85) and ~5% for Θ~1.75 against m=1 resonant resistive MHD modes, and $\bar{\beta}$~20% (Θ~1.85) against m=1 resonant ideal MHD modes, in the case of $m_\lambda=2$, $n_\lambda=1$, S_0~1 and $S=1\times10^3$. The stability beta limit to the m=1 resonant resistive MHD modes of ~5% for Θ~1.75, is smaller rather than a not optimized stable beta value of $\bar{\beta}$~5.5%, $\beta(0)$~7.8% in PRSM-RFP configuration with $S_0=0.8$, $m_\lambda=5$, $n_\lambda=2$, $\Theta=1.76$, $S=3\times10^3$. Hence, the stability beta limit is predicted to be higher in PRSM-RFP than maximum stable beta value β_{st} in finite β RFP model mentioned above. The parameter study for the optimization into higher beta is progressing by the further increase of S_0, $|F|/\Theta$ and m_λ/n_λ. In an inflated Bessel function model modified (or modified minimum energy configuration) by both the pitch function $P(r)=2(1-r^2/8-r^4/400)$, in which $\mathbf{j}\bullet\mathbf{B}/B^2$ becomes small or zero in the outer regions, and a pressure gradient to satisfy Suydam criterion, the stability beta limit is reduced to $\beta(0)$~12% (Θ~2.0) ($S=10^2$~10^3, without a vacuum edge) against m=1 resistive MHD (tearing) modes, and $\beta(0)$~17% (Θ~3.0) against m=1 ideal MHD (kink) modes [4].

5. CHARACTERISTICS OF STEADY STATE RFP REACTOR CONCEPT

The full potential of the RFP confinement concept can probably be realized by the current density profile control to stabilize high beta plasma and to attain its steady state confinement. The high beta and low external magnetic field characterizes RFP reactor concept. An expression for the bootstrap current density j_{BC} relative to the required toroidal current density j_ϕ for the target equilibrium with pressure profile $p/p_0=1-(r/r_W)^\nu$, gives $j_{BC}/j_\phi\sim(\beta_p\,\varepsilon^{1/2}/4)\nu^2/(\nu+2)$, which explicitly shows the need for high beta, low value of aspect ratio $\varepsilon^{-1}(=R/r_W)$, and steep pressure gradients. An example, the following approximation to the PRSM-RFP equilibrium with $S_0=0.8$ is assumed: β_p~20%, ν~2 and $\varepsilon^{1/2}$~0.5. For these conditions, the above expression results in j_{BC}/j_ϕ~2.5%. For steady state operation, the circulating power must be minimized if the engineering power gain Q_E (the ratio of plant gross electric power production to circulating power for sustaining operations) is to be maximized; this goal for RFP concept is achieved by minimizing not the non-inductive seed current for the bootstrap current effect, but the externally supplied toroidal magnetic field strength B_e for the paramagnetic effect. The value of B_e is ~1/10 times field strength on axis B_0 depending on RFP model. The cost of electricity (COE) depends predominantly on only two variable, Q_E and mass power density (MPD, defined as the ratio of net electric power to the grid divided by the total mass of the fusion power core) [6]. In order to minimize COE and maximize MPD, the fusion power density, averaged over the plasma volume, should be high, which means that the plasma beta should be maximized. Therefore, the paramagnetic effect in RFPs makes the compatibility of high Q_E and low COE because of the high value of toroidal beta value defined as $\beta \equiv \langle p\rangle/2\mu_0 B_e^2$.

6. SUMMARY

The obtained results are summarized as follows;

i. M=1 resonant resistive MHD modes-stable PRSM-RFP equilibrium is obtained which in the central regions of the pinch are of the form given by Taylor, in the middle regions have a flat λ profile, and in the outer regions carry no current.

ii. PRSM-RFP plasmas with $\bar{\beta}_p(=2\mu_0\langle p\rangle/B_{\theta W}^2)=16.1\%$ ($\bar{\beta}$~5.5%, $\beta(0)$~7.8%, $S_0=0.8$), $m_\lambda=5$, $n_\lambda=2$, $F/\Theta=-0.2/1.76$ are stable against m=1 resonant resistive MHD modes in the case of Lundquist number $S=3\times10^3$. The further increase of S_0, $|F|/\Theta$ and m_λ/n_λ values can be predicted to enhance the stability beta limit β_{st}, as well as for m=1 ideal kink modes. For comparison, the value of β_{st} is higher than that in a RFP model describing both parallel and perpendicular current density components.

iii. The value of β_{st} can be enhanced by widening the flat region in λ profile with FMW current drive using wave parameters such as parallel refractive index and wave power appropriate to plasma parameters.

iv. The wave power required for the enhancement of β_{st} becomes the less for the larger I_z/N at a constant plasma pressure. The larger is I_z/N, the higher is current driving efficiency and the longer is energy confinemet time as it scales $\tau_E \propto (I_z/N)^{3/2}$ with Spitzer resistivity (i.e. without dynamo-enhanced power input).

v. In the presence of positive gradient in λ profile, which is controllable by FMW current drive, the lower beta plasma ($\bar{\beta}_p=8.24\%$, $S_0=0.4$) is stable, but the higher beta plasma ($\bar{\beta}_p=16.1\%$, $S_0=0.8$) is unstable against the m=1 resonance resistive MHD modes with higher n number (for example, na/R>3) and the m=1 resonant ideal MHD modes with lower n number (na/R<3), critical n number of which might depend on λ profile.

vi. The paramagnetism effect and high beta value, rather than bootstrap current contribution, characterizes the steady state RFP reactor with the compatibility of high power gain and low cost.

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