Study of internal kink mode stability in IR-T1 tokamak

Nabizadeh F., Naghidokht A*

School of Physics, Damghan University, B. O. Box: 36716-41167, Damghan, Semnan, Iran
*****Email: ahmadnaghidokht@gmail.com*

Abstract

Internal kink mode, as an effective factor in disruptions, and it's stability in IR-T1 tokamak (with circular cross-section plasma) is studied. Due to the rapid change of this mode with the safety factor, considering a common profile for toroidal current density leads to the safety factor and growth rate of the internal kink instability profiles. With increasing of the υ values, the safety factor at inner parts of the plasma drops below one and we have the instability growth in these areas. For the smaller υ values, the mode is stable everywhere in this tokamak.

Keywords: Magnetohydrodynamic stability, Internal kink mode, IR-T1 tokamak.

Introduction

Magnetohydrodynamic (MHD) stability is essential for devices that want to steadily apply nuclear fusion, especially magnetic fusion energy. Turbulence due to MHD instabilities can take any form, but resonance occurs for instabilities that have surfaces with definite $q = m/n$ and creates certain modes of instability. The stabilization of tokamak plasma in this modes is provided by the safety factor q [1,2].

Internal kink mode $m = n = 1$ is considered as a direct cause or at least an important component in the dynamics of sawtooth oscillations in tokamak, which causes disruptions and then the catastrophic loss of plasma control. The growth rate of this mode depends to a large extent on the q profile. A very small change in q may ideally destabilize the stable equilibrium [3,4]. In tokamak IR-T1, it has been shown that the presence of modes $m = 2$ and $n = 1$, as well as $m = 3$ and $n = 2$ leads to a large disruption [5]. In the STOR-M tokamak discharges, suppression of mode perturbations (1,1), (1, 3), and (1,4) has been observed [6].

In this work, we will study internal kink mode stability in IR-T1 tokamak, which is a small, ohmically heated, air-core tokamak without copper shell and circular cross-section plasma (Table. 1).

Method

The basic variable characterizing stability, $q(r)$, is related to the toroidal current distribution. Radial profile of the safety factor $q(r)$ usually has its minimum value inside or near the magnetic axis and increases outwards. At high aspect ratio and circular cross-section, the behavior of q is simply determined as:

$$q(r) = \frac{2\pi r^2 B_\varphi}{\mu_0 R_0 I_p} = \frac{r B_\varphi}{R_0 B_\theta} \qquad (1)$$

Where B_φ , B_θ and R_0 are toroidal field, poloidal field and major radius of plasma. For a current distribution in the form:

$$j_\phi(r) = j_{\phi 0}(1 - \frac{r^2}{a^2})^\upsilon \qquad (2)$$

then using Maxwell's equations, the poloidal magnetic field profile is given as:

$$B_\theta = \frac{\mu_0 j_\phi(0) a^2}{2(\upsilon+1) r}\left(1 - \left(1 - {r^2}/{a^2}\right)^{\upsilon+1}\right) \quad r \leq a$$
$$B_\theta = \frac{\mu_0 j_\phi(0) a^2}{2(\upsilon+1) r} \qquad a < r < b \qquad (3)$$

finally, the safety factor profile, Eq. (1), is given by [7]:

$$q(r) = \frac{2\pi a^2}{\mu_0 I_p} \frac{B_\varphi\, {r^2}/{a^2}}{R_0\left[1 - (1 - {r^2}/{a^2})^{\upsilon+1}\right]} \qquad (4)$$

We will consider a very simple zero pressure cylindrical equilibrium with nearly constant current in the z direction. The plasma is contained in the region $r < a$ and the wall at $r = b$ is considered perfectly conducting. The region between $r = a$ and $r = b$ is the *vacuum* region. The magnetic field is given by:

$$\mathbf{B}_0 = \left(B_0 + B_2(r)\right)\hat{\mathbf{z}} + \mathbf{B}_\theta(r) \qquad (5)$$

where B_0 is a dominant toroidal field in a tokamak and r is the radius of the cylinder. Pushing the plasma a small distance away from its equilibrium state, thus the momentum equation becomes:

$$\rho_0 \frac{\partial^2 \boldsymbol{\xi}}{\partial t^2} = \mathbf{J_0} \times \delta\mathbf{B} + (\boldsymbol{\nabla} \times \delta\mathbf{B}) \times \mathbf{B_0} = \mathbf{F}(\boldsymbol{\xi}) \quad (6)$$

where $\boldsymbol{\xi}$ is the displacement of the plasma ($\partial\boldsymbol{\xi}/\partial t = \mathbf{v}$). Outside the plasma the vacuum field is perturbed and produces a pressure on that region. In order to matching the magnetic pressure inside and outside of the plasma, a small compressive component must be added to the plasma displacement, the magnitude of which will be determined by matching the pressure at the boundary between the plasma and the vacuum. Also, the absence of any field in the region between plasma and vacuum should be considered. Finally, the momentum equation is as follows:

$$\rho_0 \frac{\partial^2 \boldsymbol{\xi_0}}{\partial t^2} = \mathbf{F}(\boldsymbol{\xi}) = \frac{2B_0^2}{\mu_0 q R_0^2} \frac{\left(\frac{b^2}{a^2} - \frac{1}{q}\right)}{\left(\frac{b^2}{a^2} - 1\right)} \left(\frac{1}{q} - 1\right) \boldsymbol{\xi_0} \qquad (7)$$

where $\boldsymbol{\xi} = \boldsymbol{\xi_0}$ is considered. When $1 > q > (\frac{a^2}{b^2})$, we will have an internal kink instability with the following growth rate [8]:

$$\gamma = \sqrt{\frac{2B_{\varphi}^{2}}{\mu_0\rho_0 q R_0^{2}}\frac{\left(\frac{b^2}{a^2}-\frac{1}{q}\right)}{\left(\frac{b^2}{a^2}-1\right)}\left(\frac{1}{q}-1\right)} \qquad (8)$$

All parameters in equation (4) are provided in Table. 1.

Table 1. characteristic data for IR-T1 tokamak [5].

parameter	value
Major radius (R_0)	45 cm
Minor radius (a)	12.5 cm
Minor radius of vaccuum vessel (b)	15 cm
Average electron density (ρ_0)	~ (0.9)*10^19 m^{-3}
Toroidal field (B_φ)	0.75 T
Plasma current (I_p)	~ 32 kA

Results and discussion

In this section, we presnt the growth rate and safety factor profiles, Eqs. (4) and (8), in Figs. 1 and 2 to study stability of this mode in IR-T1 tokamak. This work has been done completely through programming in MATLAB software and its tools.

As the υ value increases, the central value of the safety factor ($q(0)$) decrease and in some areas reach below one, real parts for $\upsilon = 4$ and $\upsilon = 5$, which can lead to instability of the internal kink as seen in Figure 2. In fact, in Fig. 2, we have the instability growth only for $\upsilon = 4\,,5$ and for lower υ values, this mode will be stable in IR-T1 tokamak (imaginary parts in Fig 2). We notice that for all of υ values, $q(a)\sim 4$ and this crieterion is also verified before [5].

Conclusions

Ideal MHD instabilities arising from the current or pressure gradient indicate the final boundary of operational limitations for most configurations, and possible instabilities fall into the ideal and resistance mode groups. In this work we found that the internal kink instability grows only for higher υ values and as localizedly. As a consequence, this instability can be prevented by adjusting the appropriate toroidal current density profile.

Studying the temporal change of safety factor and subsequently the growth rate of internal kink instability as well as the poloidal magnetic flux functions can have more significant results for the performance of the tokamak during its discharge, which will be discussed in future works.

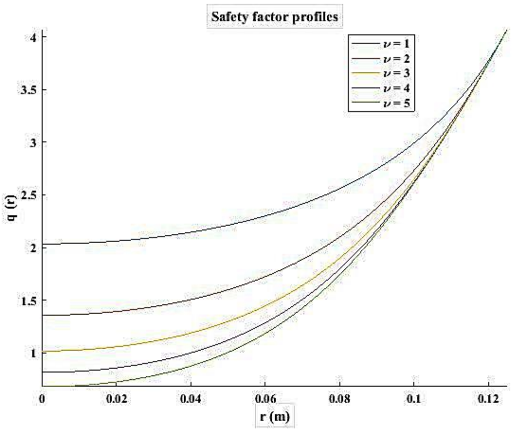

Figure 1. The safety factor profile by Eq. (4) in IR-T1 tokamak.

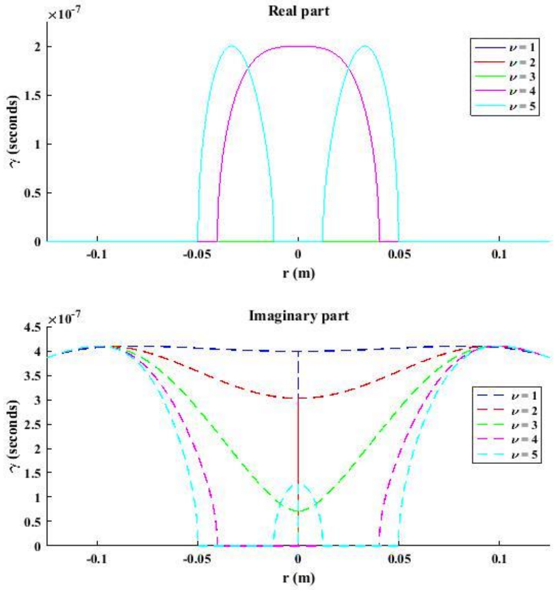

Figure 2. The growth rate of internal kink instability (Real part of Eq. (8)) and Imaginary, or stable, part of Eq. (8) for this mode in IR-T1 tokamak for values $\upsilon = 1{,}2{,}3{,}4{,}5$.

References

[1] A. Gsponer, *Physics of high-intensity high-energy particle beam propagation in open air and outer-space plasmas*, arXiv:physics/0409157v3 (2009).
[2] H. Zohm, *Magnetohydrodynamic Satbility of tokamaks*, (Wiley-VCH, Garching, 2015).
[3] V. S. Lukin, Ph.D thesis: *Computational study of the internal kink mode evolution and associated magnetic reconnection phenomena*, Princeton University (2008).
[4] H. de Blank, Ph.D thesis: *Theory of the m=1 kink mode in toroidal plasmas*, The National Uiversity in Utrecht (1990).
[5] S. Meshkani, M. Ghoranneviss and Ch. Rasouli, *Recent MCF Activities in Iran*, in the 23rd IAEA Technical Meeting on Research Using Small Fusion Devices, Santiago, Chile, March. 29-31 (2017).
[6] C. Xiao, et al., *Control of MHD Instabilities in the STORM Tokamak using Resonant Helical Coils*, IAEA pub. EXS/P5-15 (2010).
[7] M. Ghoranneviss et al., *Measurements of the Plasma Current Density and Q-Profiles in IR-T1 Tokamak*,
Journal of Fusion Energy. 29(3), 232 (2010).
[8] S. Cowley, *Lectur notes: Introduction to kink modes-the Kruskal-Shafranov limit*, UCLA (2007); J. P. Freidberg, *Ideal magnetohydrodynamics*, Plenum, 1987.