Simulations of Alfvénic Modes in TJ-II Stellarator

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ABSTRACT

Alfvénic modes are one of the subclass of instabilities prevalent in burning plasmas due to interaction of energetic particles with background plasma. In this paper we investigate the properties of these modes with 3D simulations using modeling tools STELLGAP [1] and AE3D [2] of Neutral Beam Injection (NBI) heated H-plasmas in TJ-II low-magnetic-shear flexible heliac (B_0 = 0.95 T, <R> = 1.5 m, <a> = 0.22 m). These simulations focus on modelling the experimental observations [3] for prominent modes in TJ-II plasmas. Our simulations show consistency in frequency and radial location with the measured Alfvén Eigenmodes [3]. These simulations are performed for chirping and steady modes in TJ-II discharge # 29839 at t = 1150 and 1160ms respectively.

INTRODUCTION

A. *Importance of study*

Alfvén Eigenmodes are of importance in fusion plasmas in view of next step burning plasma experiments. This is because they are likely to be excited by energetic particles and may ultimately cause losses of energetic fusion-born alpha particles in future fusion reactors. These instabilities can affect the efficiency of alpha-particle heating as well as cause damage to the first wall of the machine [4]. One of the challenges for a fusion reactor is how to contain the alpha particles in the vessel long enough for the particles to efficiently heat the plasma. Since these alpha particles can escape the fusion chamber prematurely by exciting high frequency Alfven waves and scattering of these waves to the vessel walls. The study of the confinement properties of energetic particles, and, in particular their interaction with the background plasma, is therefore a key element in the preparation for ITER and DEMO operations [4, 5]. Fortunately, effective methods exist to produce significant fractions of energetic ions already in present experiments. Although these populations differ qualitatively in their energy and pitch-angle spectra from those of fusion-alphas, they still offer an excellent opportunity to test theoretical models and codes and to develop and benchmark diagnostic techniques [4]. The first observations of Alfvén Eigenmodes (AE) in TJ-II [6, 7] demand detailed investigations of these structures for future 3D fusion devices. In this work, the properties of energetic particle driven shear Alfvén Eigenmodes (AE) measured in [3] are studied for nominal plasma parameters of Flexible Heliac TJ-II.

B. *State of the art Modelling Tools*

There are a variety of modelling tools available in the scientific community for different scales and devices. In this study, the following set of tools is used.

I VMEC is a 3D numerical model used to calculate the equilibria in 3D fusion devices, using an energy minimizing principle.

II STELLGAP [1] is a code for the calculation of shear Alfvén continua and gap formations in 3D toroidal / helical geometries.

III AE3D [2] is a code for the evaluation of Alfvén spectral properties, and mode structure in toroidal devices.

C. *Modelling of Alfvén Eigenmodes in 3D geometry*

A reduced MHD shear Alfvén model [8] is used here for the modelling of Alfvénic instabilities in TJ-II plasmas. The continuum structures are obtained from the STELLGAP code [1] and Alfvén mode structures are calculated using the AE3D code [2]. The mode structure includes the effects of couplings from the 3D equilibrium for both the Alfvén continuum and Alfvén Eigenmode calculations. The main eigen-value equation used in these tools is;

$$\omega^2 \nabla \cdot \left(\frac{1}{V_A^2}\nabla\phi\right) + (\boldsymbol{B}\cdot\nabla)\left[\frac{1}{B}\nabla^2\left(\frac{\boldsymbol{B}}{B}\cdot\nabla\phi\right)\right] + \nabla\zeta\times\nabla\left(\frac{\boldsymbol{B}}{B}\cdot\nabla\phi\right)\cdot\nabla\frac{J_{\|0}}{B} = 0$$

Here **B** is the equilibrium magnetic field; B is its magnitude, $J_{\|0}$ is the equilibrium parallel current, Φ is the electrostatic potential, while ζ is the toroidal angle coordinate, $V_A^2 = B^2/\mu_0\rho_m$ is Alfvén speed and $\rho_m = n_{ion}m_{ion}$ is ion mass density. Setting coefficient of highest order radial (ρ) derivatives to zero leads to the continuum equation. These are the continua of shear Alfvén problem [1] and provide an initial guess for the location and frequency gaps where eigen functions of the Alfvénic instabilities exist.

D. *Alfvén Eigenmodes in TJ-II Stellarator*

TJ-II discharge # 29839 is interesting due to its distinct feature, specifically chirping and steady-frequency modes coexisting at the same time in this discharge. The experimental observations of Alfvén mode structures in this discharge are presented in [3]; in this work modelling of chirping and steady modes is presented. Experimental results confirm the signatures of these modes because of the stronger coherence of Heavy Ion Beam Probe (HIBP) and Mirnov Probe (MP) data as shown in Fig (1) left panel and the zoom of the prominent mode in right panel. The first results of 3D modelling of these modes along generation of gap structures are presented in Section E.

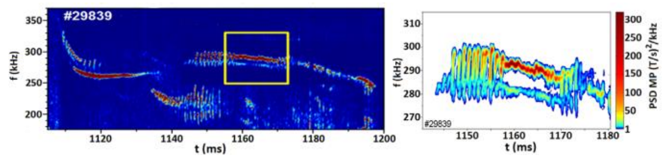

Fig. 1 Experimental observations of Alfvén Eigenmodes used in these simulations for TJ-II Stellarator Discharge # 29839 [3].

E. *Results from STELLGAP simulations*

Separate simulations of these experimental results for chirping and steady modes at t = 1150 and 1160 ms respectively have been performed by using the simulation tools discussed in Section B. Corresponding simulated Alfvén continuum gap structures for chirping and steady modes are plotted in Fig. 2 and 3 respectively.

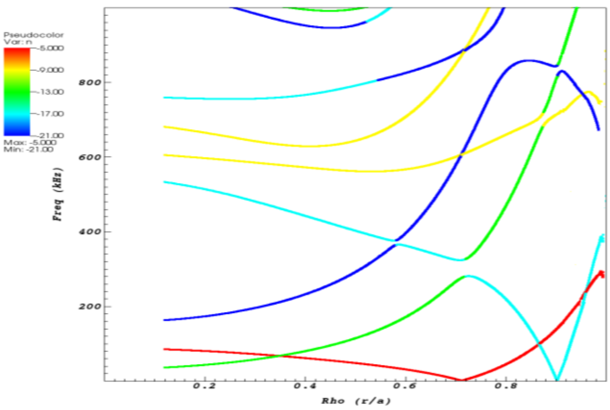

Fig. 2 Alfvén continuum gap structures for chirping phase of mode at t = 1150ms.

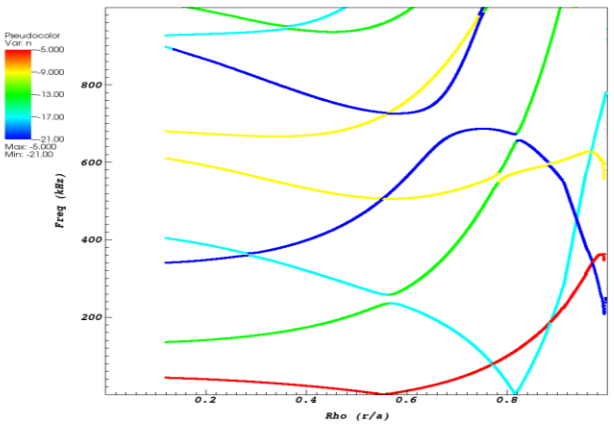

Fig. 3 Alfvén continuum gap structures for steady phase of mode at t = 1160ms.

The prominent toroidal mode numbers are shown distinctly with color coding in the graphs.

F. *Results from AE3D simulations*

To investigate the mode structures and their profiles, AE3D simulations have been performed for the cases presented in section E. Corresponding results are presented in Figs 4 and 5.

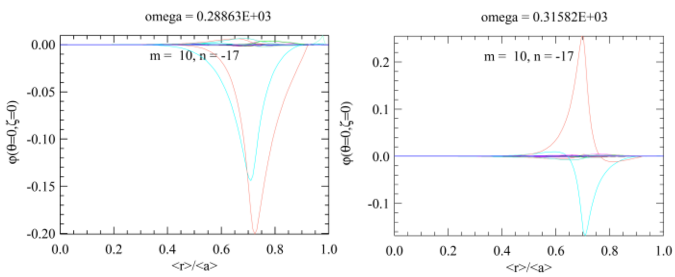

Fig. 4 Alfvén Eigenmodes for chirping modes.

In both the cases of chirping and steady modes, there is single prominent mode. In the chirping phase, the modes (m = 10 and n = -17) have two different frequencies of 289 and 316 kHz, located at radial position ρ = 0.7. While in the steady phase, the same mode (m = 10 and n = -17) appears with a lower frequency of 254 kHz at smaller radial location ρ = 0.55. It can be seen that the mode (m = 10 and n = -17) is prominent in both cases and is comparable with experimental results, although there is a decrease in frequency from 289 to 254 kHz.

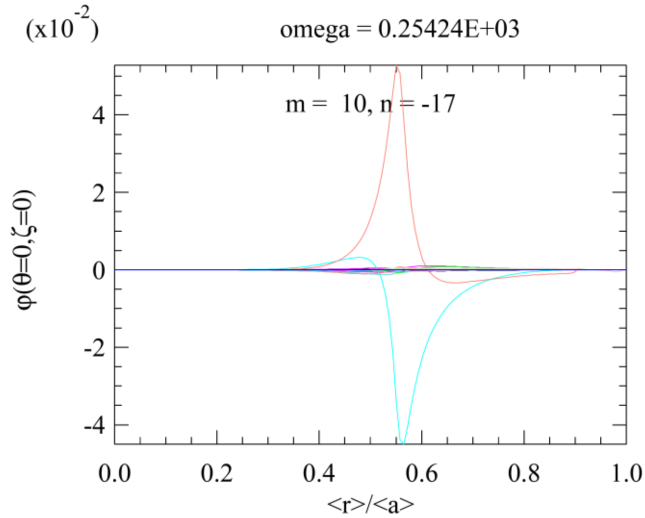

Fig. 5 Alfvén Eigenmode structure for the steady phase of the mode.

TABLE I
SUMMARY OF THESE MODES

Mode type	Prominent mode numbers (m, n)	Frequency (kHz)		Radial location (ρ)
Chirping	(10, -17)	289	316	0.70
Steady	(10, -17)	254		0.55

G. *Summary and Future Enhancement*

It can be inferred from these simulations that the modes move radially inward when there is a transition from chirping to steady frequencies. Moreover, the frequencies of modes are also decreasing significantly. Interestingly the mode (m = 10 and n = -17) remains persistent during this transition.

This work will be extended to investigate other properties and types of Alfvén eigenmodes in TJ-II plasmas. Active interaction of the energetic particles with these modes and resonance calculations for these interactions will be explored. Furthermore, the comparison of these calculations with the experimental data will be addressed.

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Author biography

Allah Rakha was born in Jhang, Pakistan, in 1985. He received the M.Phil. degree in Physics from the Pakistan Institute of Engineering & Applied Sciences (PIEAS), Islamabad in 2008, and the M.S. degree in Nuclear Fusion & Engineering Physics from the Ghent University, Belgium, in 2015.

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