Modelling of Alfvénic instabilities in complex toroidal magnetic geometries for fusion

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I. INTRODUCTION

Nuclear fusion is the way to produce enormous amounts of relatively clean energy by fusing light hydrogen isotopes, deuterium (D) and tritium (T), into heavier helium nuclei (He) born at energy 3.5 MeV, and a very energetic neutron (n) of 14 MeV. To achieve the goal of fusion, a mixture of ionized gases i.e. a plasma consisting of D and T ions, is heated to extreme temperatures of $T = 10^8$ K in specific magnetic fusion devices [1]. The magnetic nuclear fusion devices can have quite complex magnetic field topologies, including nested magnetic surfaces, islands and stochastic domains. To achieve the high temperatures, the fusion plasmas are heated with auxiliary heating systems generating fast ions and/or with fusion produced alpha-particles (He at 3.5 MeV). The fast particles interact with plasma in confining magnetic field and often excite magnetohydrodynamic (MHD) instabilities in the range of Alfvénic frequencies. These MHD instabilities may degrade the confinement of energetic particles (EPs) [2]. Furthermore, these instabilities in complex 3D magnetic geometries may be more dangerous because of the additional coupling between toroidal harmonics which generate specific Alfvén gaps [3] in the Alfvén continuum with some discrete spectrum of weakly-damped Alfvén Eigenmodes (AEs). These AEs are widely investigated in complex toroidal magnetic geometries both in experiments and theory. Numerical modelling and simulations [4] are playing an important role in the explanation of current experimental findings and for predictions in future devices.

In this work we investigate AEs [5] in a 3D toroidal magnetic geometry of the flexible TJ-II heliac shown in Figure 1. TJ-II is a machine with a four period ($N_{fp} = 4$) magnetic field of $B_0 = 0.95$ T, with a low magnetic shear, major radius, $R_0 = 1.5$ m and averaged minor radius, $\langle a \rangle = 0.22$ m. Main advantage of the TJ-II flexibility is the ability to provide a platform for investigating various types of Alfvénic modes in quite different magnetic configurations.

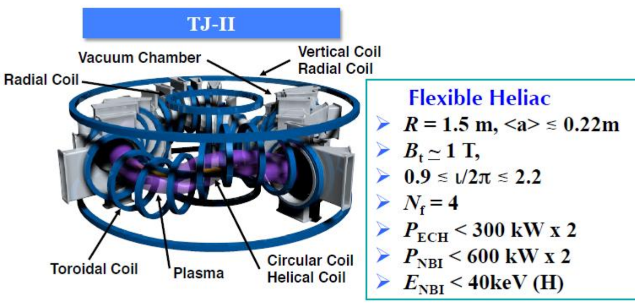

Figure 1: Schematic diagram of TJ-II flexible heliac located at CIEMAT Madrid, Spain.

By varying the magnetic configuration, the TJ-II machine can investigate plasma heating by energetic ions produced with neutral beam injection (NBI), which mimic the mechanism of self-heating with energetic alpha-particles and associate instabilities and demonstrate the fusion self-heating capability of the complex field devices. Here, the comparison of Alfvénic instability modelling results with the experimental findings for TJ-II dynamic discharges (with varying magnetic configuration) is presented. The simulation results for AEs in this complex geometry are in good agreement with the experimental findings. In this paper, the modelling of Alfvén continuum structures in TJ-II plasmas is performed with the STELLGAP [6] code and AEs structures with the spectral code AE3D [7]. Our modelling is focused on investigating the possible gaps in Alfvén continuum structures and AE profiles with their frequencies, combination of prominent mode numbers and radial localization.

II. PHYSICS OF ALFVÉN EIGENMODES

The AEs are coherent MHD waves that exist in toroidal magnetic fusion devices. In a toroidal magnetic geometry, the intersection points of the counter propagating Alfvén waves with equivalent parallel wave vectors $|k_{||}|$ generate the Alfvén gaps in the continuum structures. These gaps are the prominent locations where the AEs can exist and get excited by energetic particles. The lack of axial symmetry and strong shaping associated with complex toroidal 3D magnetic geometries further enhance the coupling between these gaps and generate a more condensed set of prime locations for exciting the AEs. Finding these gap structures and prominent AEs in them with their potential profiles is the main work presented in this paper. The Alfvén continuum solver STELLGAP solves a symmetric generalized matrix eigenvalue continuum equation, by giving the continuum mode structure and eigen frequency. The calculation of discrete AEs is considerably more complicated than calculating the continuum structures. A reduced MHD formulation [8] in the spectral code AE3D is employed to calculate the AEs structures, potential profiles and, radial extents. . The main eigen-value equation which performs these tasks in the AE3D code comes from the vorticity equation and the ideal Ohm's law.

III. MODELLING OF ALFVÉNIC INSTABILITIES IN THE TJ-II STELLARATOR

The AEs are modeled in TJ-II by considering discharges in which Alfvén mode activity was experimentally observed. In this paper, we focus on two dynamic discharges to investigate the effect of complex magnetic configurations on AEs.

The dynamic discharges were performed at TJ-II to investigate the chirping behavior of NBI-driven Alfvén modes caused by magnetic configuration variations in the TJ-II stellarator. The experiments found the coexistence of steady and chirping modes [9] as shown in Figure 2. For the modelling of chirping and steady modes, the two similar evolving discharges with dynamically increasing and decreasing iota values, the shots 29834 and 29839 are considered exhibiting the coexistence of chirping and steady modes. These discharges are interesting due to their important features of simultaneous existence of chirping and steady frequency modes.

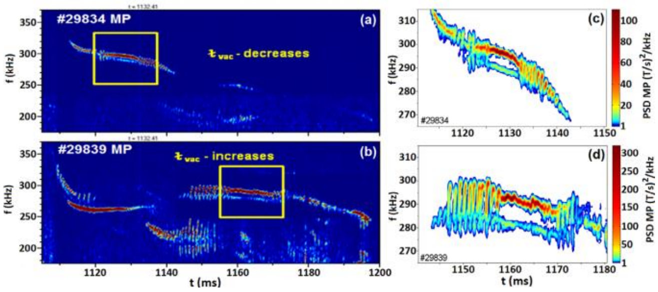

Figure 2: Experimental observations of Alfvén eigenmodes (AEs) modelled using Reduced MHD simulations for TJ-II stellarator discharge 29834 and 29839 [9].

The calculation of the spectra and the radial location of the modes at three different time slices to map the full spectrum of observed modes. For discharge 29834, the simulations are done at t = 1125, 1130 and 1135 ms and similarly for discharge 29839 at t = 1150, 1160, 1170 ms. The simulation results for this section are summarized in Table 1, which are consistent with the experimental findings. The Alfvén continuum gap structures and AE mode structure for one of the modeled cases are presented in Figure 3.

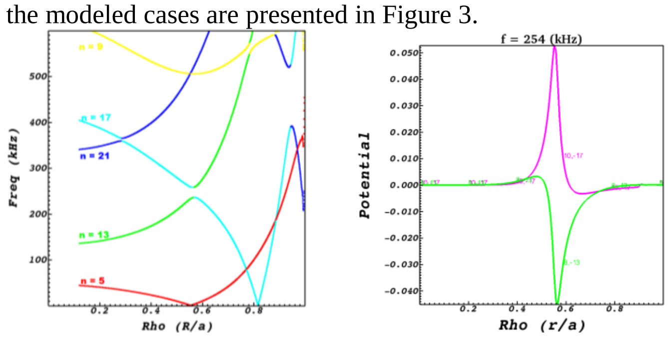

Figure 3: Alfvén continuum gap structures in left and AE structure for steady mode in discharge 29839 at t = 1160 ms. The prominent toroidal mode numbers are shown distinctly with color coding in the graphs

TABLE I
SUMMARY OF MODELLING RESULTS , WHERE, 'S' AND 'C' CORRESPOND TO THE STEADY AND CHIRPING TYPES OF MODES, RESPECTIVELY

Discharges	Modes (m, n)	Frequency (kHz)		Radial location (ρ)
#29834	(11, -19)	276(s)	292(c)	0.65/0.75
	(2, -3)	272(c)	275(s)	0.40/0.45
#29839	(10, -17)	289(c)	254(s)	0.70/0.55
	(8, -13)	251(s)	234(c)	0.55/0.80

IV. SUMMARY AND FUTURE EXTENSIONS

The modelling and simulation analysis of TJ-II dynamic plasmas support the coexistence of chirping and steady AEs. Modelling has revealed that the modes with steady frequencies are relatively localized close to plasma center with lower frequencies, given the higher density at these radial positions. On the other hand the modes with chirping or bursting behavior are localized at larger values of ρ and with relatively lower frequencies.

The extension of this work will lead to model similar discharges with different iota profiles to explore the effect of magnetic configuration on AEs. The fast ions density and pressure effects will also be investigated using non-linear modelling and wave-particle interaction. The resonant interaction of EPs with such modes will be also studied. Furthermore, the comparison of these calculations with the experimental data in TJ-II, and in other 3D devices will be addressed.

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Author biography

Allah Rakha, received the M.Phil. degree in Physics from the Pakistan Institute of Engineering & Applied Sciences (PIEAS), Islamabad in 2008 with full fellowship from federal government of Pakistan. He also obtained the M.S. degree in Nuclear Fusion & Engineering Physics from the Ghent University, Belgium, in 2015 with two years Erasmus Mundus fellowship. Since October 2008, he has been working as Lecturer in Physics at Department of Physics & Applied Mathematics (DPAM), PIEAS Islamabad. In 2016, he joined Barcelona Supercomputing Center (BSC) as PhD researcher in Fusion group under the supervision of ICREA Prof. Mervi Mantsinen. He won a prestigious AGAUR FI predoctoral grant from the Catalan government to partially fund his PhD. His current research interests include plasma physics, MHD of fusion plasmas, and Alfvénic instabilities in stellarator devices. He also closely works under EUROfusion education work package (WPEDU).