An island induced Alfvén eigenmode and effects of nonaxisymmetry on fast ions in the RFP

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Abstract:

Fast ions are well confined in the stochastic magnetic field of the multiple-helicity (MH) RFP, with fast ion confinement times routinely a factor of 5 to 10 higher than thermal confinement time [1]. This leads to a substantial fast population during high power neutral beam injection (NBI) in the MST. There are several effects on the background plasma, including enhanced toroidal rotation, electron heating, and an altered current density profile. The abundant fast particles are observed to excite multiple beam driven instabilities that lead to a saturated core fast ion density[2]. The amplitude of the core-most tearing mode is substantially reduced. Recent theoretical work analytically computes the effect of a magnetic island on the shear Alfvén continuum[3] and may explain some previously unresolved Alfvénic activity observed in MST plasmas during neutral beam injection. Consideration of the previously-ignored core-localized n=5 magnetic island leads to theoretical Alfvén continua that provide a gap in which the observed n=4 Alfvénic bursts reside. Numerical simulations using the STELLGAP/AE3D codes, as well as a new code called SIESTAlfvn have identified the bursts as the first observation of a magnetic Island-induced Alfvén Eigenmode (MIAE). The MIAE arises from a helical coupling of mode numbers, similar to the helicity-induced Alfvén eigenmode, but occurs in the core of an island. The observed frequency of bursting n=4 Alfvénic modes fall within the island-induced gap over a wide range of MST operating parameters. A subtle ambiguity exposes interesting physics of the reversed field pinch: when the n=5 rational surface is very near the magnetic axis, a weak magnetic shear exists; a helical perturbation without reconnecting into a magnetic island is possible, and experimental measurements to date cannot clearly distinguish between the two cases. The observed n=4 activity could be a helicity-induced Alfvén eigenmode (HAE) with similar frequency and mode structure. Work supported by USDOE.

1 Introduction

The presence of an island-induced gap and discrete eigenmode in the shear Alfvén continuum [4] is an important new observation. The associated magnetic fluctuations can be a powerful transporter of energetic ions and will likely influence any magnetically confined burning plasma. The magnetic island-induced Alfvén eigenmode (MIAE) has been observed in stellarator [5] and very likely in RFP [6] could possibly exist. experiments.

As the role of 3D magnetic fields in tokamaks grows in prominence (for example in mitigation of ELMs, or the expected saturated 3/2 NTM in the ITER hybrid scenario) associated changes in Alfvénic spectral properties, including MIAEs, are anticipated.

Evidence of a magnetic island influence on the Alfvén continuum in tokamaks is given by a strong variation of BAE frequency with tearing mode amplitude measured in EAST, FTU and TEXTOR [7,8]. The island causes a minimum continuum accumulation point frequency upshift; the location of the minimum frequency moved from the rational surface to the separatrix. More generally, three dimensional structures inherent in all magnetic configurations (e.g. ripple or regions of stochasticity) affect the confinement and stability of fast particles within a plasma. The NBI-heated RFP is a useful device for testing the effects of magnetic islands and other axisymmetry-breaking on fast ions.

2 Features of NBI-heated RFP

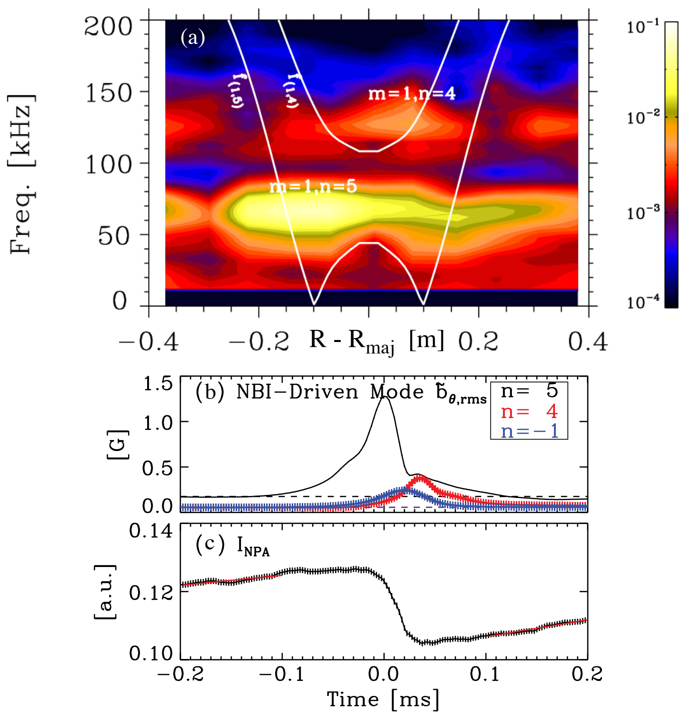

FIG. 1: (a) Measured EPM and MIAE in MST, with time resolved magnetics (b) and core fast ion content (c).

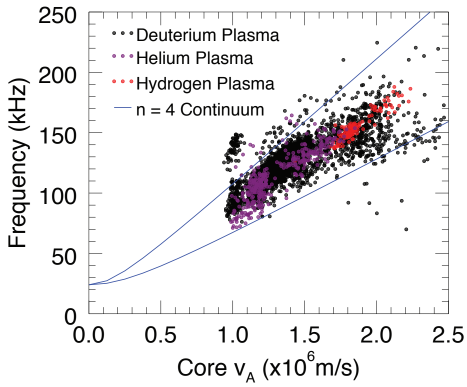

FIG. 2: The measured n=4 frequency lies between the j_{in}=1 and j_{in}=2 branches of the MIAE.

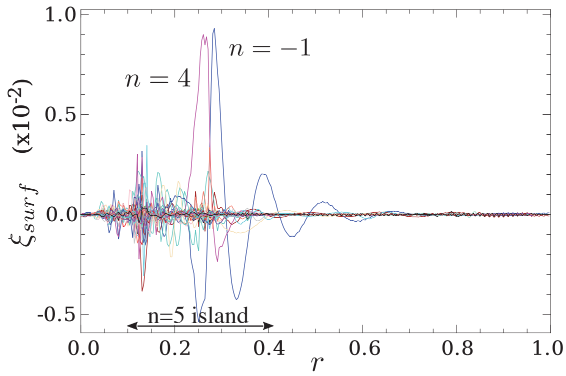

FIG. 3: Numerically computed MIAE mode structure in MST plasma.

The core of the NBI-heated RFP plasma exhibits several unique variants of axisymmetry-breaking magnetic perturbations that impact fast ion confinement and stability. The appearance of magnetic islands and associated magnetic stochasticity is controllable. A well-formed core-localized island is adjustable in size, ideal for study of the MIAE. While the RFP is nominally axisymmetric, in the quasi-single-helicity limit the dominant island envelops the magnetic axis, producing a stellarator-like three dimensional geometry.

Figure 1 is an example of energetic particle modes (m=1,n=5) and suspected MIAEs (m=1,n=4) driving fast ion transport in the Madison Symmetric Torus (MST)[9] In Fig. 1a), the time-averaged amplitude of electron density fluctuations correlated with the bursting modes is plotted versus frequency and radius[10] In Fig. 1b) the time evolution of the edge-measured magnetic fluctuation is plotted for three modes with toroidal mode numbers n =5, 4, and -1. Fast ions are rapidly lost during the peak magnetic activity, indicated in Fig. 1c): the NPA signal is a measure of core-localized, high pitch NBI-born fast ions which drive these instabilities.

The unperturbed Alfvén continuum $f = \frac{k_{||}v_A}{2\pi} = \frac{(m-nq)B_\theta}{2\pi r|B|}v_A$ is also plotted in Fig. 1a); the m=1, n=5 branch has a zero where $q = 1/5$ and a resonant tearing mode (m=1,n_0=5) can exist. The SIESTA code reconstructs the 3D MHD equilibrium with an n=5 island, which alters the n=4 branch of the Alfvén continuum and opens a gap at the island core. Experimental measurements to date cannot formally rule out an n_0=5 ideal helical core perturbation (as opposed to a tearing-driven magnetic island) in these discharges. An ideal perturbation would likely recategorize the bursty n=4 mode as an HAE, though recent analytical and numerical results are consistent with the MIAE.

A new analytic formulation[3] computes the continuum frequencies on helical magnetic flux surfaces located within island separatrices. At the O-point, $f = \sqrt{f_{BAE}^2 + \frac{n_0^2 j_{in}(j_{in}+2)}{16} q_0'^2 w^2 k_{||}^2 v_A^2}$ where w is the island width, j_{in} is an integer that denotes the branch of the continua, q_0' and f_{BAE} are the magnetic shear and minimum BAE frequency at the rational surface. A controlled scan of the core Alfvén speed for discharges with an off-axis $q = 1/5$ rational surface and bursting n=4 modes is shown in Fig. 2. The measured n=4 frequency falls between the j_{in}=1 and j_{in}=2 branches of the

MIAE. Numerical simulations using a new code (SIESTAlfven) have computed the mode structure of the MIAE, plotted in Fig. 3.

The mode has both n=4 and n=-1 components that are centered within the n_0=5

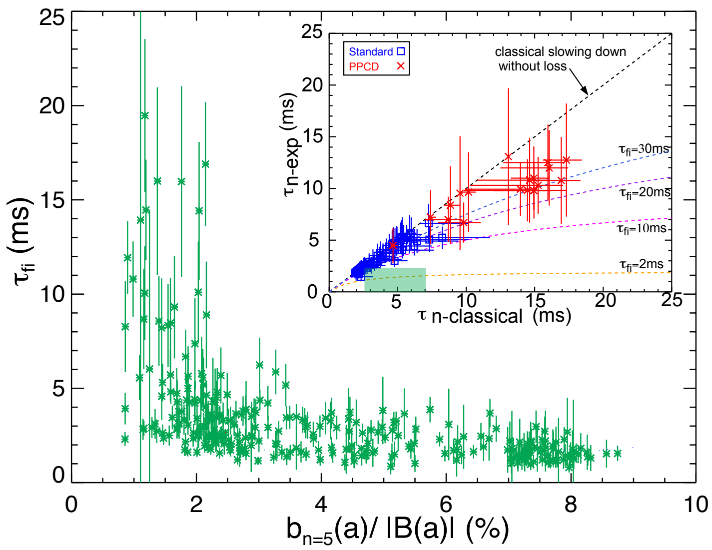

FIG. 4: Coherent 3D core perturbation reduces τ_{fi}, while τ_{fi} approaches the classical limit in a stochastic field (inset).

magnetic island that are in agreement with the measurements in Fig. 1.

Fast ion confinement is reduced when the 3D magnetic perturbation is large and coherent. This can result from neoclassical and fluctuation-induced transport. Non-intuitively, the fast ion confinement approaches the classical limit in the presence of multiple small tearing modes that cause magnetic stochasticity. Plotted in green in Fig. 4 are measured confinement times (τ_{fi}) of tangentially co-injected 25keV D+ as a function of 3D helical core perturbation. The confinement responds inversely, occupying the shaded green box in the inset figure. The remainder of data in the inset are a measure of fast ion confinement over a range of stochasticity in the RFP brought about by multiple overlapping tearing modes.

Blue points represent modestly stochastic standard discharges, while red points are current-profile-controlled discharges with reduced stochasticity. In these two cases, $\tau_{fi} >> \tau_{thermal}$ showing a relative insensitivity to magnetic stochasticity.

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