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by

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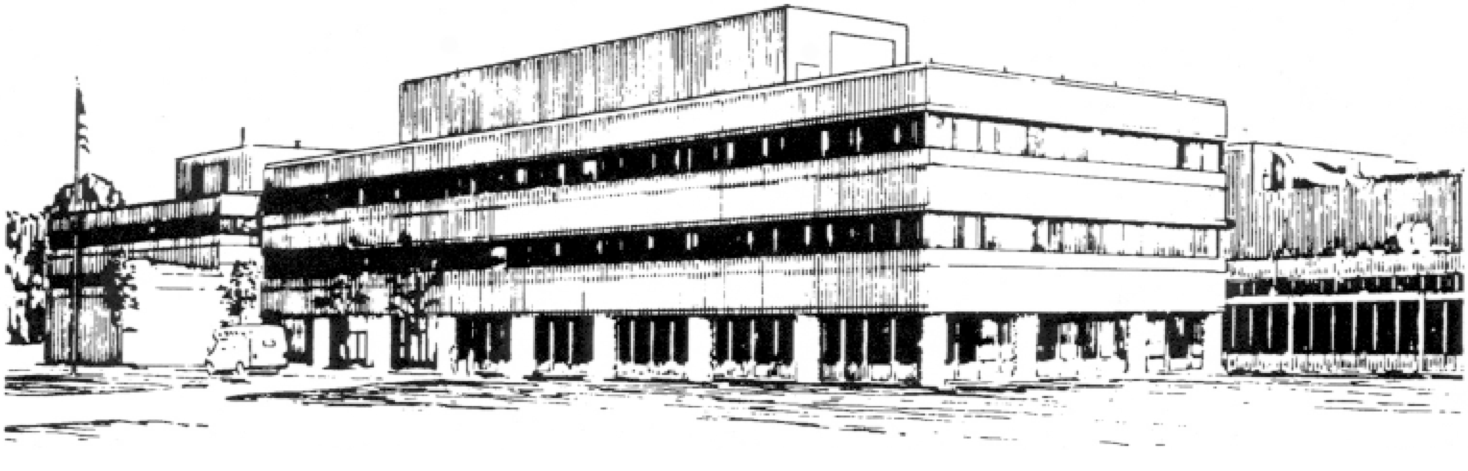

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Energetic Particle Effects Can Explain the Low Frequency of Alfvén Modes in the DIII-D Tokamak

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Abstract

During beam injection in the DIII-D tokamak, modes with lower frequencies than expected for toroidicity-induced Alfvén eigenmodes (TAE) are often observed. We present the analysis of one of these "beta-induced Alfvén eigenmodes" (BAE) with a high-n stability code HINST that includes the effect of the energetic ions on the mode frequency. It shows that the "BAE" could be the theoretically predicted resonant-TAE (RTAE), which is also called an energetic-particle modes (EPM).

I. INTRODUCTION

During intense neutral beam injection into high-beta DIII-D plasmas, an instability with a frequency about half of the frequency of the toroidicity-induced Alfvén eigenmode (TAE) was observed [1]. In its most virulent form, the instability caused large losses of fast ions. Based on ideal MHD analysis and its appearance at high beta [2], the new instability was dubbed a beta-induced Alfvén eigenmode (BAE). Later, three alternative theoretical identifications were proposed: a kinetic ballooning mode [3], a mode that propagates at the ion thermal speed [4], and an Alfvén mode whose structure and frequency are modified by the fast-ion population. The fast-ion modified instability was called a resonant-TAE (RTAE) in Ref. [5] and an energetic-particle mode (EPM) in Refs. [6], [7], [8]. An extensive database of frequency measurements from DIII-D was compared with simplified frequency scalings based on these four theories, but none of the simple models adequately explained all of the observations [9]. On balance, the data appeared most consistent with the hypothesis that the instability was an RTAE/EPM, but more detailed comparisons were clearly required.

This work reports the first of such comparisons. A non-perturbative fully kinetic code HINST [10], which stands for *hi*gh-n *st*ability code, is used to compute the expected frequency and stability of the RTAE in a typical DIII-D plasma with slightly negative shear and with unstable "BAE" activity. As we will show, the code successfully finds an unstable mode with a frequency that is consistent with the measured frequency. The toroidal mode numbers n of the unstable modes are also close to the experimental observations.

II. EXPERIMENT: DESCRIPTION OF THE INSTABILITY

The case selected for the comparison is a double-null divertor, deuterium plasma that is heated by 9.5 MW of 76 keV deuterium neutral beams. At the time of interest, the safety factor profile is weakly reversed (Fig. 1d) and the plasma has entered an ELM-free H-mode, so the stored energy, neutron rate, and density are rapidly increasing. As shown in Fig. 1, the central ion temperature is approximately 10 keV and there is an edge pedestal in the density and temperature profiles. Because the density is still relatively low and the confinement is high, the classically-expected beam pressure (Fig. 1c) is a significant fraction of the total plasma pressure. Phenomenologically, "BAEs" are often observed in plasmas with large beam-ion pressure. [9]

Instabilities are observed by a Mirnov coil that is situated about 45° degrees below the outer midplane (Fig. 3a). Three types of coherent magnetic activity are observed (Fig. 2). Low frequency ($<$ 20 kHz), low n (n =1-2) modes appear intermittently. A fairly steady $n = 5$ mode with a frequency of 90-100 kHz is also seen. Bursts of activity appear between 150-250 kHz (Fig. 3c). Virtually all of the bursts have a dominant $n = 4$ or $n = 5$ mode with a frequency between 170-200 kHz. Clusters of modes reminiscent of the first "BAE" observations (Figs. 1 and 6 of Ref. [9]) occur on some bursts; on other bursts, such as the one shown in Fig. 2, additional peaks above 200 kHz are seen. The $\sim$ 95 kHz $n = 5$ mode and many of the $\sim$ 180 kHz $n = 4$ modes are also observed on reflectometer channels but, because of the weak density gradient in the plasma interior, it is not possible to reconstruct the spatial eigenfunction from the available data. The comparison of the experimental mode frequency (which is measured in the laboratory frame) with the predicted frequency (which is computed in the plasma frame) is complicated by the Doppler shift, which causes the experimental frequency to be a function of position. [11] For strongly rotating plasmas, the measured frequency in the plasma frame f_{pl} is approximately $f_{pl} \simeq f_{lab} - nf_{rot}$, where f_{lab} is the observed frequency in the laboratory frame and f_{rot} is the toroidal rotation frequency of the plasma. Since the central toroidal rotation frequency is 33 kHz in this discharge, the $\sim$ 180 kHz modes must be propagating in the plasma frame ($f_{lab} - nf_{rot} > 0$), while the $\sim$ 95 kHz mode may be stationary. Our attention in this study focuses on the propagating $\sim$ 180 kHz modes. In previous work, the appearance of modes in this frequency band generally correlates with reductions in the the volume-average neutron rate. [9] In this case, the measured neutron rate is 90-100% of the classically-expected rate predicted by the code TRANSP, [12] so global losses of beam ions are small. On the other hand, the bursts in Fig. 3c correlate with slight reductions in the neutron rate, so some redistribution of energetic beam ions probably occurs at each burst.

III. THEORY: ALFVÉN SPECTRUM ANALYSIS

The Alfvén stability of this discharge at 1190 ms (Fig. 3) is analyzed with the HINST code [10], which is a nonperturbative fully kinetic code. This code is able to reproduce RTAE branches with a drive from fast particles. Calculations of mode drive and damping include bulk plasma and fast particle Finite Larmor Radius (FLR) effects. Radiative damping supported by trapped electron collisional effects and ion Landau damping are also incorporated. Even though HINST robustly finds solutions with high toroidal n numbers that have radially localized mode structures, it can be used for medium-n to low-n modes in the local version, i.e. without resolving the two-dimensional ($2D$) mode structure. HINST employs a shooting technique to find the mode frequency, growth rate and one-dimensional ($1D$) mode structure in ballooning coordinates. Note that the global HINST $2D$ solution requires radial localization of the mode and high toroidal mode numbers n.

HINST uses the $s - \alpha$ model for the plasma equilibrium [20], which assumes isotropic plasma pressure. Since RTAEs have a ballooning structure similar to TAEs, i.e. with the maximum mode structure at the low magnetic field side of the plasma, the local equilibrium can be approximated as isotropic. Empirically, the "BAE" is destabilized by circulating beam ions [9], so the beam-ion distribution function is approximated as a slowing-down distribution consisting solely of passing ions.

The results of the analysis are shown in Fig.4. Consider first the results of the local (1D) calculations, which are represented by + symbols in Fig. 4. In the region of low fast particle pressure gradient, the RTAE frequency of the local solution is inside the toroidicity-induced gap of the Alfvén continuum, as predicted by previous theory [21]; however, the mode is weakly damped ($\gamma < 0$) in these regions. On the other hand, where the gradient of fast particle pressure is strong near $r/a = 0.6$, the mode is unstable ($\gamma > 0$) and the local frequency ω drops into the lower continuum of ideal MHD. Both the maximum of γ and a local minimum of ω occur in this strong gradient region, which is also near the minimum in the q profile.

Presumably, the observed mode is destabilized in this region of maximum drive near $r/a = 0.6$. Since the frequency of the local solution changes significantly on a short radial scale in this region, we must consider the two-dimensional structure of the eigenfunction and the associated modifications to the mode frequency. An estimate of the global (2D) frequency can be obtained from the WKB formalism [22] [19]. We need to apply the following quantization condition

$$\int nqd\theta_k = k\pi, \tag{1}$$

where θ_k is the ballooning variable responsible for the mode radial envelope and is a parameter in the local eigenmode equation, k is the radial mode number, and the integral is taken along the constant frequency of the local solution $\omega = \omega(r, \theta_k)$. The path of integration in Eq.(1) depends on the function $\omega(r, \theta_k)$, and can have so-called open or closed trajectories in (r, θ_k) space. The first case corresponds to a function $\omega(r, \theta_k)$, which has local minima and is similar to our 1D result shown in Fig.(4). Further calculations can be simplified by expanding the numerically-obtained local frequency ω near its minima, which is also near the most unstable region, i.e. $r_0/a = 0.6$:

$$\Omega \equiv \frac{\omega}{\omega_{A0}} = \Omega_0 + X(r - r_0)^2 a^{-2} + Y\theta_k^2, \tag{2}$$

where the frequencies are normalized to the central Alfven frequency ω_{A0} and Ω_0, X, and Y are constants.

The discharge under consideration has a q-profile that, in the vicinity of its minima, can be approximated with good accuracy by the simple formula $q = q_{min} + 8.1(r - r_{qmin})^2$, where $q_{min} = 1.7$, and $r_{qmin} = 0.53$. For the experimentally observed $n = 5$, the local frequency is fitted to the parabolic dependence in minor radius and in θ_k using the least square method, which results in $\Omega_0 = 0.412$, $X = 27.4$, $Y = 0.0188$. With these parameters, the global frequency can be easily derived from from the quantization condition Eq.(1), which gives for the first radial mode (i.e, $k = 1$), $\Omega_1 = 0.50$ and, for the second radial mode ($k = 2$), $\Omega_2 = 0.58$. Note that there is no third mode since the "potential well" described by the dependence Eq.(2) is shallow in the direction of θ_k, so that the second mode has a frequency close to the edge of the well. The other result from the application of Eq(1) is the mode location, which is limited by two turning points $r_1 = 0.543$ and $r_2 = 0.655$ for the mode with $\Omega_1 = 0.5$.

The predictions for other toroidal mode numbers (Fig.5) are qualitatively similar to the ones shown in Fig.4 for $n = 5$. The code predicts that low toroidal mode numbers should be more unstable than higher mode numbers; the predicted frequency ω is also lower. Inclusion of two-dimensional effects raises the predicted frequency, as it did for the $n = 5$ mode. For example, at $n = 7$, we obtain $\Omega_0 = 0.47$, $\Omega_1 = 0.55$, with localization between $r_1 = 0.548$ and $r_2 = 0.65$.

IV. COMPARISON BETWEEN THEORY AND EXPERIMENT

The theoretical predictions of the previous section are in reasonable agreement with the experimental observations. If we assume that the ~ 180 kHz mode is excited in the region of maximum fast-ion pressure gradient, the measured frequency in the plasma frame is 130 ± 10 kHz, with the uncertainty being associated with uncertainty in the rotation frequency. (Variations in mode frequency and mode number between bursts result in a similar error estimate.) The predicted frequencies are slightly lower: $f_{pl1} = 98$ kHz for the first radial mode and $f_{pl2} = 114$ kHz for the second radial mode. A reduction in beam pressure caused by redistribution of the beam population could easily raise the prediction to be consistent with experiment. Based on this analysis, it seems likely that the observed instability corresponds to the second radial mode, which is also unstable and has a radially broader structure that could produce a larger edge signal than the first radial mode. Another important parameter is the magnetic shear, which may alter the predictions when slightly changed. We conclude that the predicted frequency is consistent with the observed frequency within experimental uncertainties.

The code predicts that $n = 4$ should be more unstable than higher values of n. Experimentally, the largest mode in the 150-250 kHz band has $n = 3 - 5$ at each burst, with $n = 4$ being most common.

In summary, local analysis of a DIII-D discharge with "BAE" activity finds an unstable RTAE with frequency and mode number comparable to the experimental observations. This lends credence to the hypothesis that the "BAEs" are Alfvén modes whose frequency is strongly modified by the fast-ion population. In future work, the predictions of a global, non-perturbative code should be compared with internal measurements of the eigenfunction.

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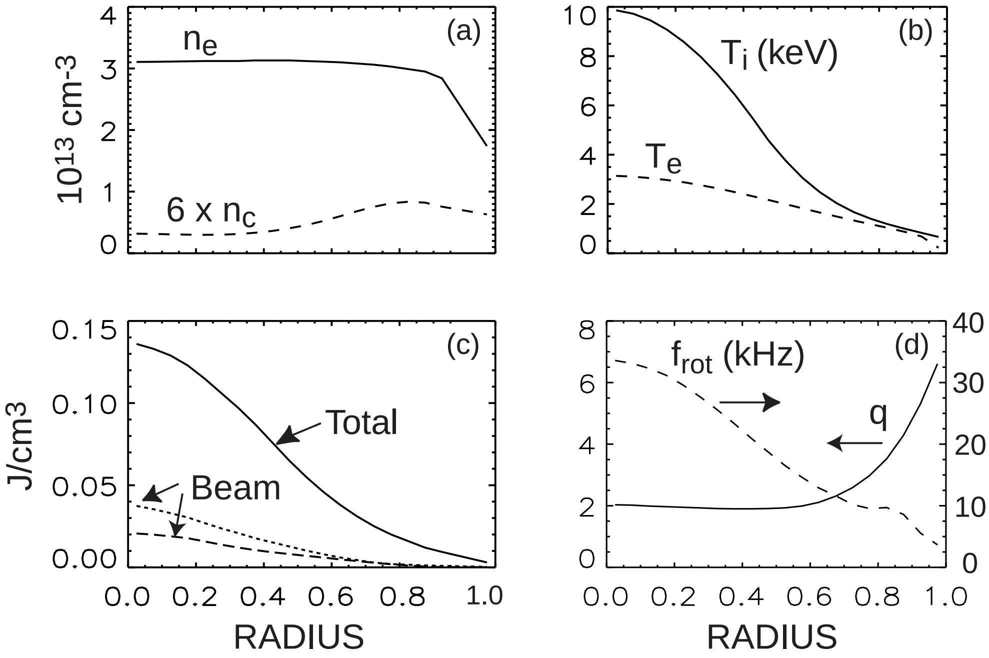

FIG. 1.

Plasma profiles at 1190 ms as a function of the normalized square root of the toroidal flux. (a) Electron density (solid) from Thomson scattering [13] and interferometer [14] measurements and carbon density (dashed, multiplied by six) measured with charge-exchange recombination (CER) spectroscopy. [15] (b) Deuterium ion temperature (solid) inferred by TRANSP [12] from CER measurements of the carbon temperature and electron temperature (dashed) from Thomson scattering and electron cyclotron emission [16] measurements. (c) Total (solid), perpendicular beam-ion (dotted), and parallel beam-ion (dashed) energy density as computed by TRANSP assuming classical beam-ion confinement. (d) Safety factor (solid) from an EFIT equilibrium reconstruction [17] that uses magnetics and motional Stark effect (MSE) [18] data and toroidal rotation frequency from CER measurements (dashed). Toroidal field $B_T = 1.6$ T, plasma current $I_p = 1.2$ MA.

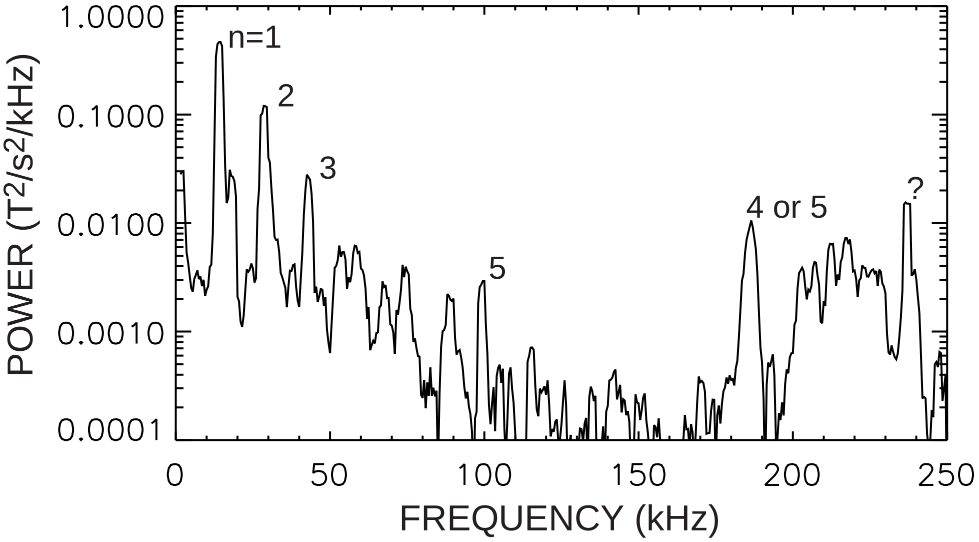

FIG. 2. Cross power spectrum of two magnetic probes that are toroidally separated by 15° at 1190-1192 ms. The numbers beside the peaks represent the toroidal mode number.

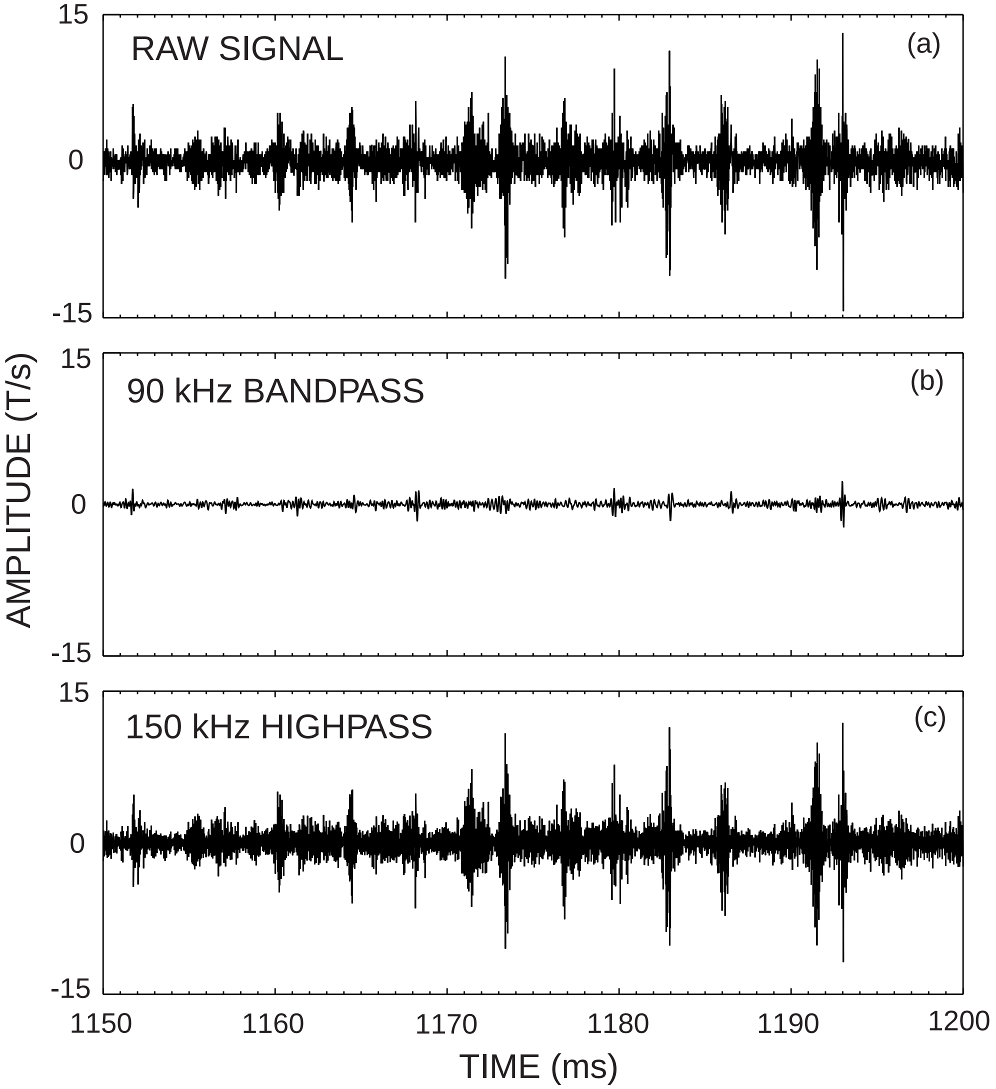

FIG. 3. Magnetic probe signal that is (a) unprocessed, (b) digitally filtered with a 45-135 kHz bandpass filter and (c) digitally filtered with a 150 kHz highpass filter. Although the $n = 5$, $\sim$ 95 kHz mode varies in amplitude, the signal is dominated by bursts of “BAE” activity with $f_{lab} > 150$ kHz.

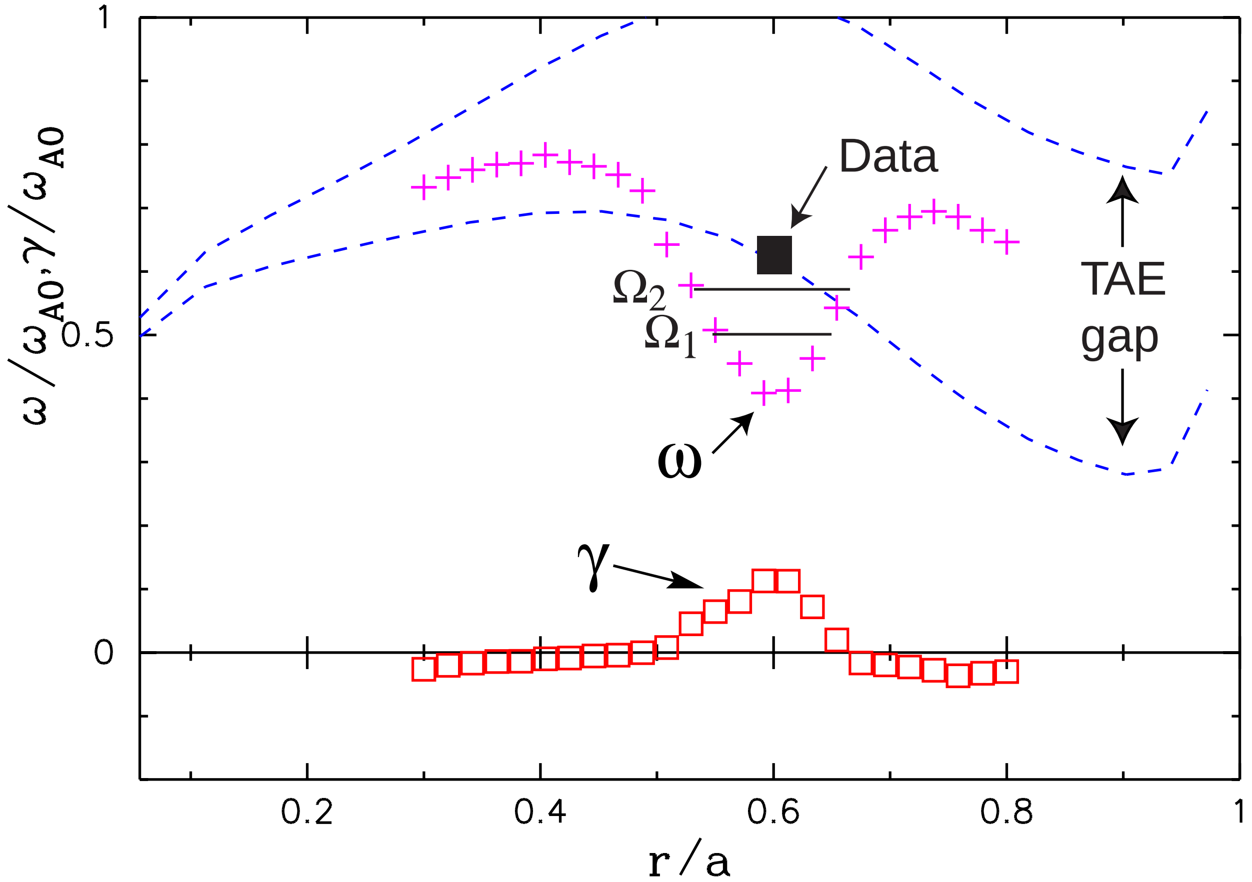

FIG. 4. Localized calculations of the RTAE eigenfrequency ω (cross) and growth rate γ (square) for the $n = 5$ mode as a function of minor radius. The dashed lines indicate the boundaries of the toroidicity-induced gap in the Alfvén continuum. The solid lines represent the first and second radial modes with frequencies Ω_1 and Ω_2 of the global WKB analysis. The solid square indicates the measured frequency in the plasma frame, $f_{pl} = f_{lab} - nf_{rot}$; the uncertainty is comparable to the size of the symbol. The central Alfven frequency is $\omega_{A0} = 1.23 \times 10^6 rad/sec$.

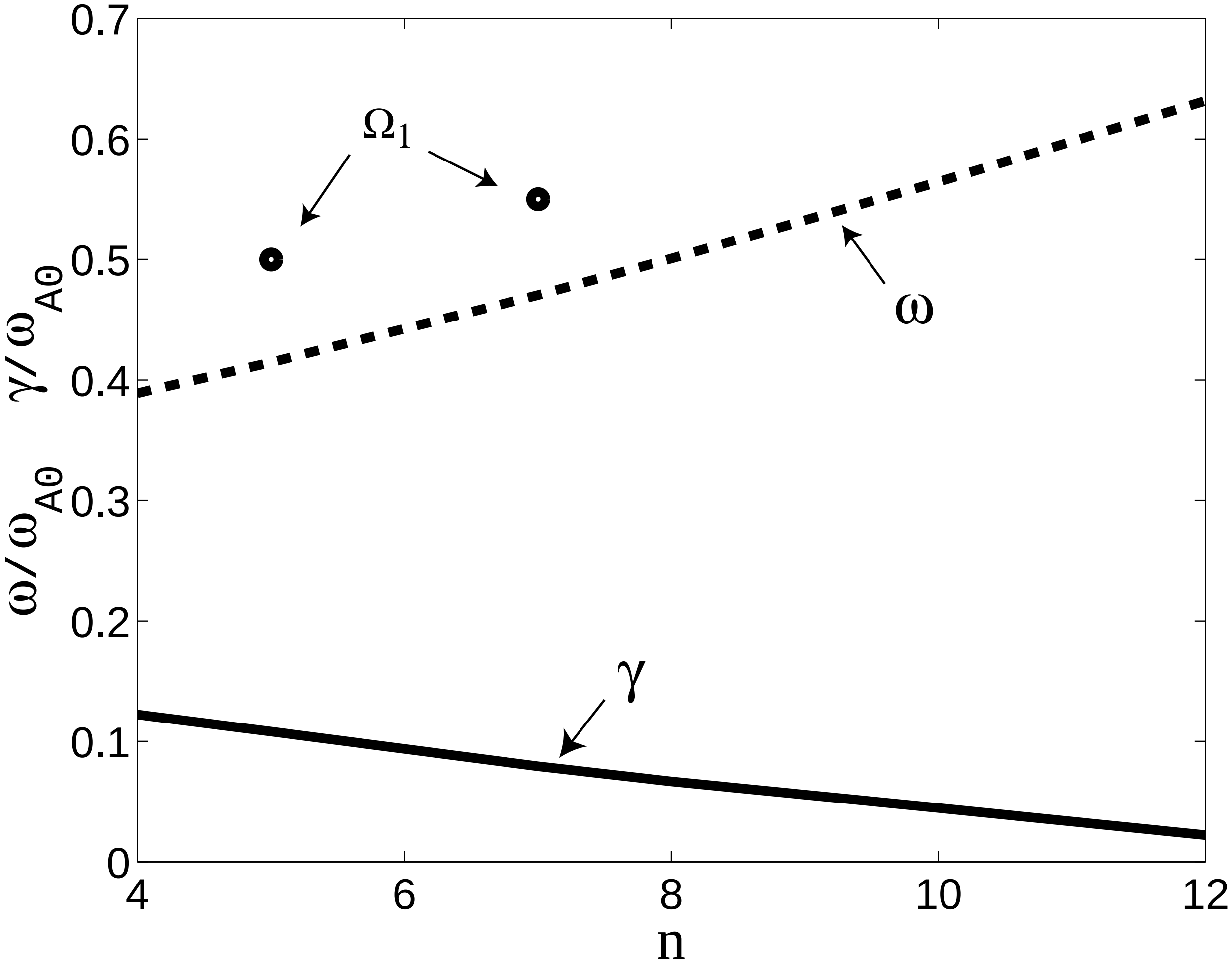

FIG. 5. Predicted RTAE eigenfrequency ω and growth rate at the location of maximum γ. Shown also are the frequencies of the global WKB solutions for the first radial modes Ω_1 at $n = 5$ and $n = 7$.

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