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ABSTRACT

In this Letter we have investigated the effect of reversing the direction of the magnetic field and plasma current on JET, hence the ion ∇B-drift direction, on the instability threshold of Toroidal Alfvén Eigenmodes (TAEs) with toroidal mode number (n) in the range n = 3 ÷ 10. These modes are driven by MeV-energy protons produced by minority H(D) Ion Cyclotron Resonance Frequency heating. A larger fast ion drive is found to be required to destabilise the modes when the magnetic field and plasma current are reversed with respect to the usual JET configuration (i.e., when the ion ∇B-drift is directed away from the divertor), with the difference decreasing for increasing n.

INTRODUCTION AND BACKGROUND.

Understanding and controlling the interaction between alpha particles and modes in the Alfvén frequency range is a crucial issue for ITER and future magnetic fusion reactors, as these modes can be driven unstable up to amplitudes at which they could cause radial transport of the αs themselves. Experimental measurements of the instability threshold of Alfvén Eigenmodes (AEs) driven by MeV-energy ions and their dependence on the background plasma parameters and configurations are therefore needed so as to verify the available calculations and guide further developments. In this Letter we analyse the dependence of the instability threshold of Toroidal Alfvén Eigenmodes (TAEs) on the direction of the magnetic field and plasma current, hence the ion ∇B-drift direction.

In the standard JET operating regimes the magnetic field and plasma current are negative, i.e., they are directed counter-clockwise when the toroidal cross-section of JET is viewed from above, and the ion ∇B-drift is then correspondingly directed towards the divertor. The ion ∇B-drift direction is thought to be an important parameter for accessing the high-confinement regime known as H-mode [1, 2]. As previously reported in Refs.[3, 4] for JET ohmic limiter discharges, for very similar background plasma parameters and eigenfunctions, the damping rate of n=1 TAEs is measured to be a factor three larger when the magnetic field and plasma current are reversed together, i.e., when the ion ∇B-drift is directed away from the divertor. A theoretical explanation for these measurements is still lacking, other than the simple observation that the ion ∇B-drift terms can in principle be included in gyro-kinetic codes (such as PENN [5], and the more recent LIGKA [6]), whereas fluid codes only include equilibrium gradients depending on the density and temperature. We also note that in JET the plasma helicity is conserved when reversing the toroidal magnetic field (i.e., the toroidal plasma current is also correspondingly reversed), and the limiter discharges used for the measurement of the n=1 TAE damping rate were largely up-down symmetric. Hence, in principle there could only be a minimal effect coming from the specific ion ∇B-drift terms present in the gyro-kinetic codes because of these dominant up/down symmetries. This observation has been the main motivation for continuing our studies on the role of the ion ∇B-drift terms on the TAE stability.

A possible explanation for the difference in the measured γ/ω for n=1 TAEs can be associated to the observation of different flows at the plasma edge and scrape-off layer for Forward and Reverse B-field Experiments (FBE and RBE cases, respectively), hence with the ion ∇B-drift directed to and away from the divertor, respectively [7,8]. In addition to a possible direct effect on the TAE damping rate, these flows also change the e-folding length for the edge density from the scrape-off layer towards the first wall [7,8], hence possibly affecting the interaction of the TAE modes with the Alfvén continuum at the plasma edge.

1. MEASUREMENT OF THE TAE INSTABILITY THRESHOLD.

To provide further insights into the role of the magnetic field direction, plasma current and ion ∇B-drift direction on the TAE stability, we have considered here the experimental measurements of the TAE instability threshold as a function of the toroidal mode number, in the range $|n| = 3 \div 10$. TAE modes with higher-n are more localised towards the plasma centre, hence less sensitive to edge effects than more global, lower-n, TAEs. These $|n| = 3 \div 10$ modes are destabilised by the MeV-energy protons (H) produced by the H(D) minority Ion Cyclotron Resonance Frequency (ICRF) heating scheme in a Deuterium (D) plasma. For all the cases considered here, the q-profile was monotonic and one single ICRF antenna frequency was used with dipole phasing to produce an ICRF power deposition profile peaked on the magnetic axis.

Figures 1(a), 1(b) and 1(c) show the measurement of the AE mode activity for one FBE and two RBE representative cases. We note that for the two RBE cases a different spectrum is excited at different levels of the ICRF heating power (P_{RF}), due to the differences in the background plasma parameters, hence in the damping and drive for the modes.

2. ESTIMATE OF THE FAST ION DRIVE.

In order to make a meaningful comparison between the FBE and RBE cases, it is essential that the continuum and mode radial structure be sufficiently similar for the various n-modes. The continuum and the radial mode structure were calculated with the CSMISH [9] and MISHKA-1 [10] codes, respectively, which do not include an e-folding length for the edge density profile from the scrape–off layer towards the first wall.

Figure 2 and fig.3 show a comparison between the continuum and the radial mode structure for representative $|n| = 3 \div 8$ TAEs in the FBE and RBE cases, respectively, for those modes whose calculated frequency best matches the measured mode frequency in the corresponding discharges. A strong similarity between the TAE wavefield in the FBE and RBE regimes can be noticed. The $|n| = 3 \div 8$ modes are those most represented in our database, but these results also apply for the $|n| = 9$ and $|n| = 10$ TAEs, which are less frequently observed. We also note that, to avoid non-physical results due to the finite number of poloidal harmonics considered in our analysis, the continuum calculations had sometimes to be cut around $x = 0.9$. Here x is the radial coordinate, defined as the square-root of the normalised poloidal flux.

The strength of the local fast ion drive required to destabilise a mode can be estimated by the quantity $\alpha_{FAST}(r) = -R_0q^2(r)(\delta\beta_{FAST}(r)/\delta r)$ [11]. Here R_0 is the position of the magnetic axis, r the radial coordinate along the minor radius, and q is the safety factor; $\beta_{FAST} = 2\mu_0 p_{FAST}/B^2$ is the fast ion normalised pressure, $p_{FAST} = n_{FAST}(T_{\perp FAST}+T_{\parallel FAST}/2)$, and n_{FAST}, $T_{\perp FAST}$ and $T_{\parallel FAST}$ ($<<T_{\perp FAST}$) are the fast ion density, perpendicular and parallel temperature, respectively. Hence, when calculated at the mode onset and averaged over the radial mode structure, $\alpha_{FAST}(n)$ represents the minimum drive from the fast ions that is required to overcome the damping for a TAE with a given n.

Figure 4 shows the summary results of our database, which includes 29 RBE and 46 FBE X-point discharges (hence no more up-down symmetric) with a monotonic q-profile, covering a wide range of background plasma parameters (magnetic field, plasma current, density and temperature profiles, ICRF and neutral beam heating power). In fig.4 the quantity $<a_{FAST}>$ is computed at the mode onset and it is given by:

$$<\alpha_{FAST}> = R_0\int_0^1 dxx\kappa(x)\xi_r(x)q^2(x)\frac{\delta\beta_{FAST}(x)}{\delta x}\Bigg/\int_0^1 dxx\kappa(x)\xi_r(x) \tag{1}$$

Hence $<\alpha_{FAST}>$ results from an average over the mode displacement $\xi_r(x)$ (as shown in fig.3(a) and fig.3(b)), to account for the differences in the calculated mode structure. In Eq.(1) $\kappa(x)$ is the elongation of the individual flux surfaces, introduced here to reproduce the main features of the JET toroidal geometry and increase the accuracy of our calculation. $\beta_{FAST}(x)$ has been evaluated using the power deposition profile calculated from the hot plasma ICRF wave dispersion relation to deduce $T_{\perp FAST}$ and $T_{\parallel FAST}$, which, together with the magnetic measurement of the fast ion energy content and the H_α/D_α data, lead to an estimate of n_{FAST} [3, 12, 13]. The value of $\beta_{FAST}(x = 0)$ is also verified against direct measurements of the fast ion perpendicular temperature and density made with an high energy neutral particle analyser following the method described in [14, 15].

The results presented in fig.4 then fully reflect the differences in the AE spectrum that were already apparent from fig.1 when comparing two particular RBE cases. The scatter in fig.4 (indicated by the vertical bars) is due to variations in the background plasma parameters (as shown in figs.1(b) and 1(c), for instance), which may also cause differences in the damping of the modes. The results presented in fig.4 show that the ranges of $<\alpha_{FAST}>$ required to drive unstable TAEs in the FBE and RBE directions overlap significantly as the background plasma parameters are changed throughout this scan. Nevertheless, the $<\alpha_{FAST}>$(RBE) required to destabilise TAEs is systematically larger than $<\alpha_{FAST}>$(FBE), a result which is consistent with the three-fold larger γ/ω that was measured for the n=1 TAEs in the RBE scenario. Also, the difference in $<\alpha_{FAST}>$ decreases for increasing n's.

SUMMARY AND CONCLUSIONS.

In summary, for JET plasmas with a monotonic q-profile, a larger fast ion drive is found to be required to destabilise TAEs with $|n| = 3 \div 10$ when reversing the direction of the magnetic field and plasma current, i.e., when the ion ∇B-drift is directed away from the divertor, with the difference increasing for decreasing n. This result is consistent with previous measurements of γ/ω for stable n = 1 TAEs actively driven with in-vessel antennas. We suggest that the different flows measured at the plasma edge and scrape-off layer for the forward and reversed magnetic field (and ion ∇B-drift) directions may play an important role in modifying the TAE stability, either directly on the mode damping rate or through a modification of the Alfvén continuum, thus affecting the TAE edge damping mechanisms, such as continuum damping [16] and mode conversion to kinetic Alfvén waves [17, 18]. Intuitively, high-n, thus more core localised, TAEs will be less affected by edge damping mechanisms than TAEs with a lower n, which are typically more global modes. This is qualitatively consistent with the observation that the difference in the TAE instability threshold between forward and reversed magnetic field increases for decreasing n. Hence, the measurements of the dependence of the damping rate and the instability threshold on the ion ∇B-drift direction as a function of the toroidal mode number can be used to test the predictions of fluid and gyro-kinetic models of the AE wavefield. In this respect, the new semi-analytic kinetic model recently proposed by Fu and co-authors [19] has the potential to lead to significant progress.

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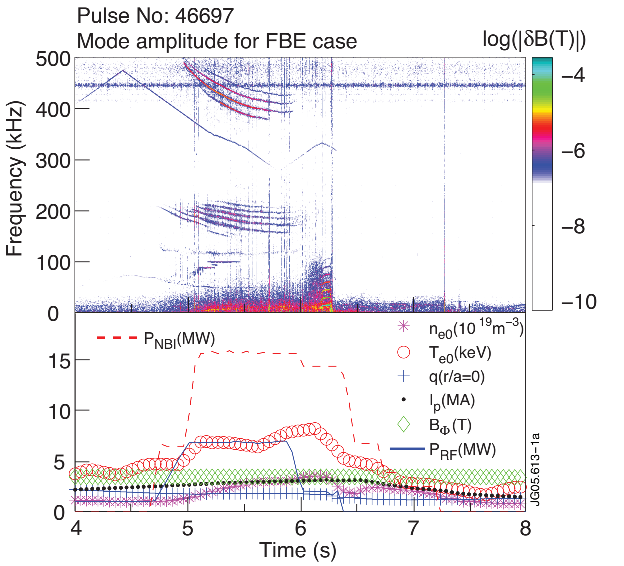

Figure 1(a): Measurement of the AE activity for the FBE case Pulse No: 46697: $n = 3 \div 8$ TAEs are excited in the frequency range 150÷220kHz, with the $n = 4$ mode first becoming unstable at $P_{RF} \approx 3.5$MW. Here n_{e0} and T_{e0} are the central electron density and temperature, I_p and B_ϕ the plasma current and magnetic field, and $P_{NBI} \approx 6.5$MW is the Neutral Beam Heating power.

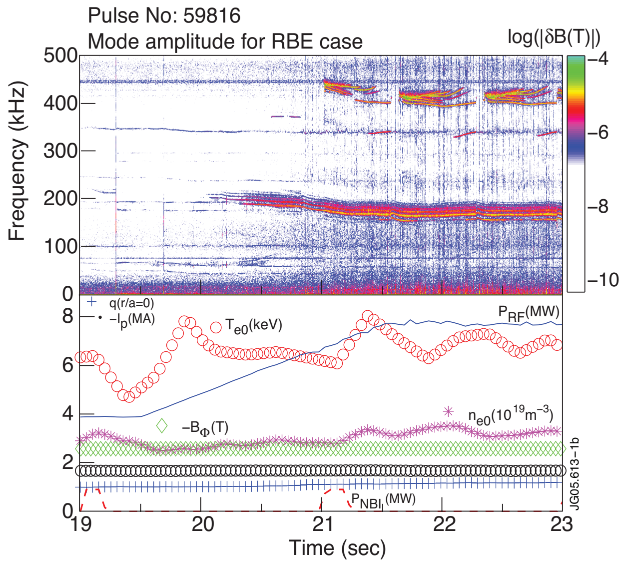

Figure 1(b): Measurement of the AE activity for the RBE case Pulse No: 59816: $|n| = 3 \div 10$ TAEs are excited in the frequency range 160÷230kHz, with the $|n| = 5$ mode first becoming unstable at $P_{RF} \approx 5$MW. The notation for the background plasma parameters is the same as in fig.1A.

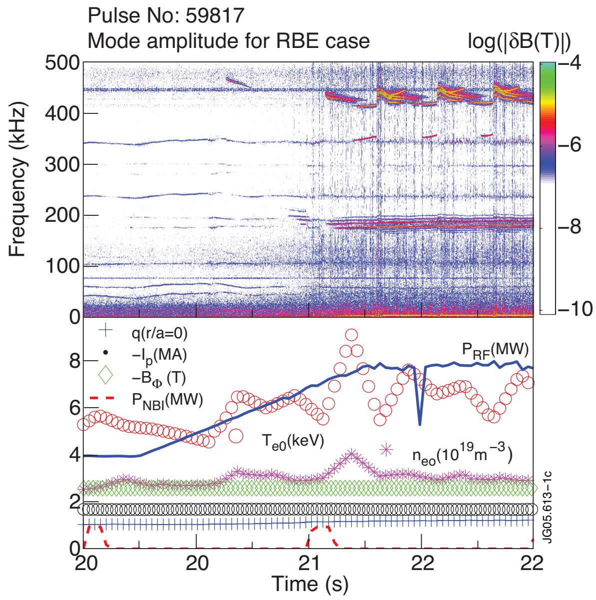

Figure 1(c): Measurement of the AE activity for the RBE case Pulse No: 59817: $|n| = 5 \div 9$ TAEs are excited in the frequency range 170÷200kHz, with the $|n| = 8$ mode first becoming unstable at $P_{RF} \approx 6.5$MW. The notation for the background plasma parameters is the same as in fig.1(a).

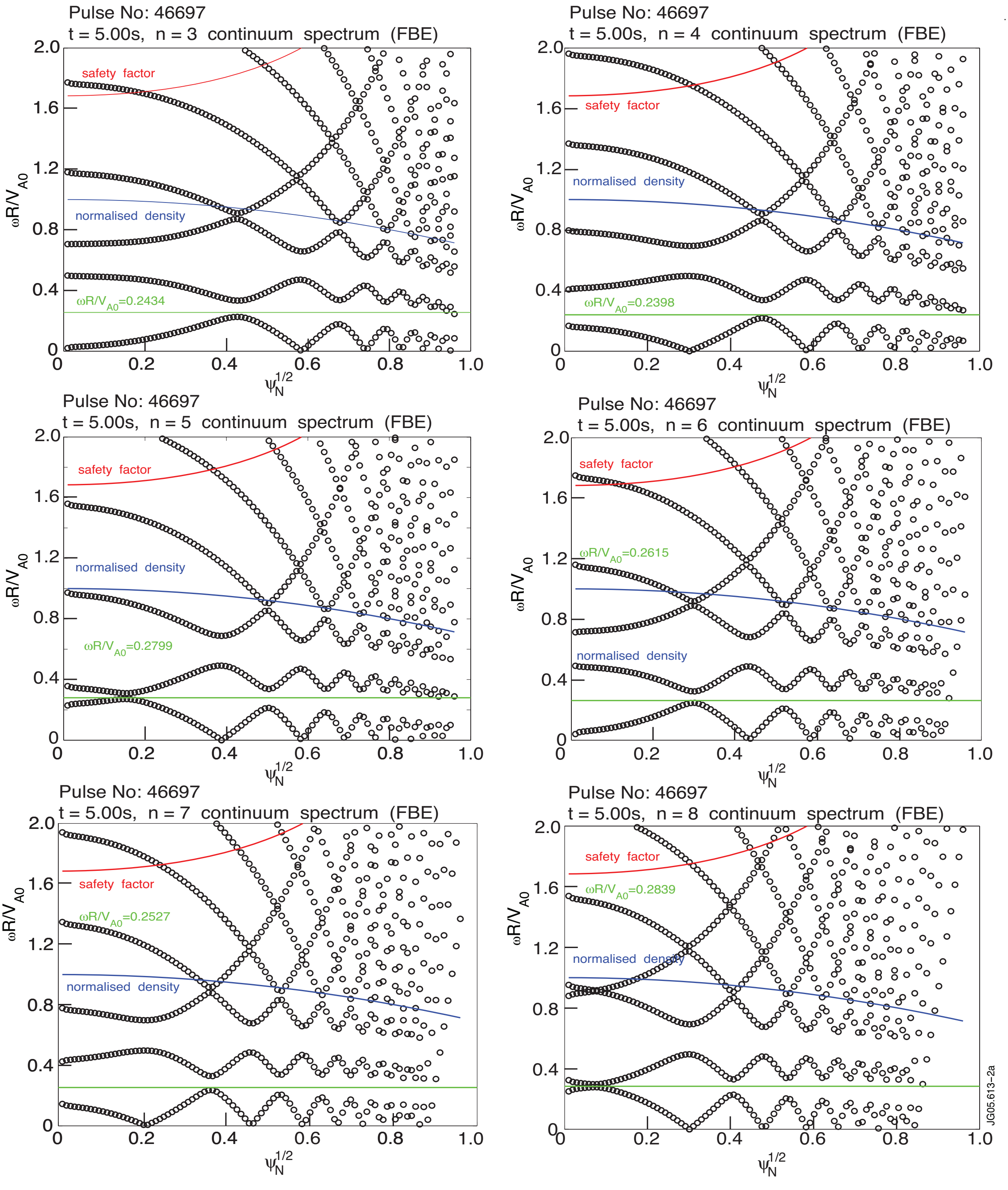

Figure 2(a): The $n = 3 \div 8$ TAE continuum spectrum for the representative FBE case Pulse No: 46697. Here and in figs.2(b), 3(a) and 3(b) $x = \sqrt{\psi_N}$ is the normalised poloidal flux, which is used as the radial coordinate in the CSMISH and MISHKA-1 calculations.

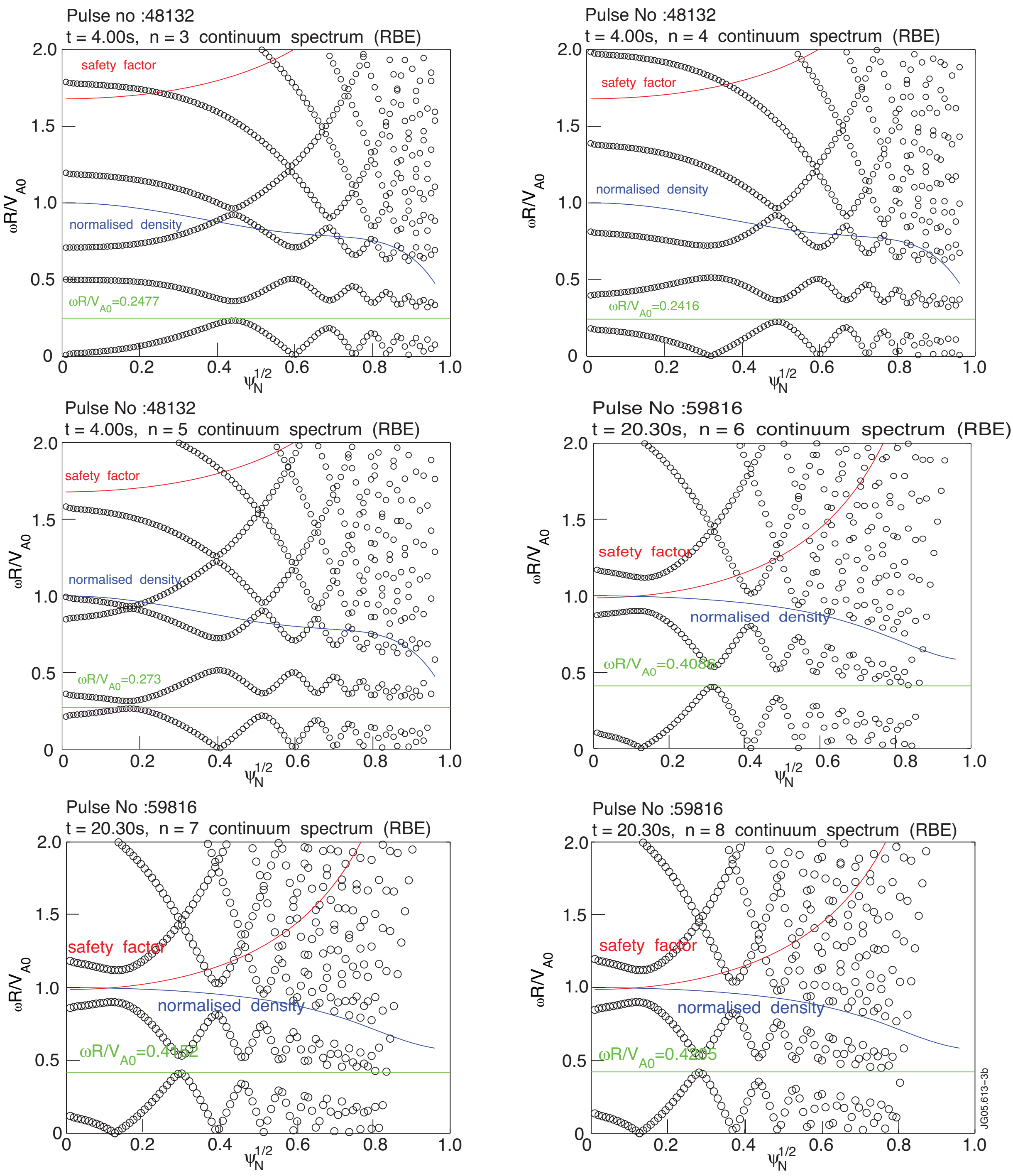

Figure 2(b): The $n = 3 \div 8$ TAE continuum spectrum for the representative RBE cases Pulse No: 48132 ($|n| = 3 \div 5$) and Pulse No: 59816 ($|n| = 6 \div 8$).

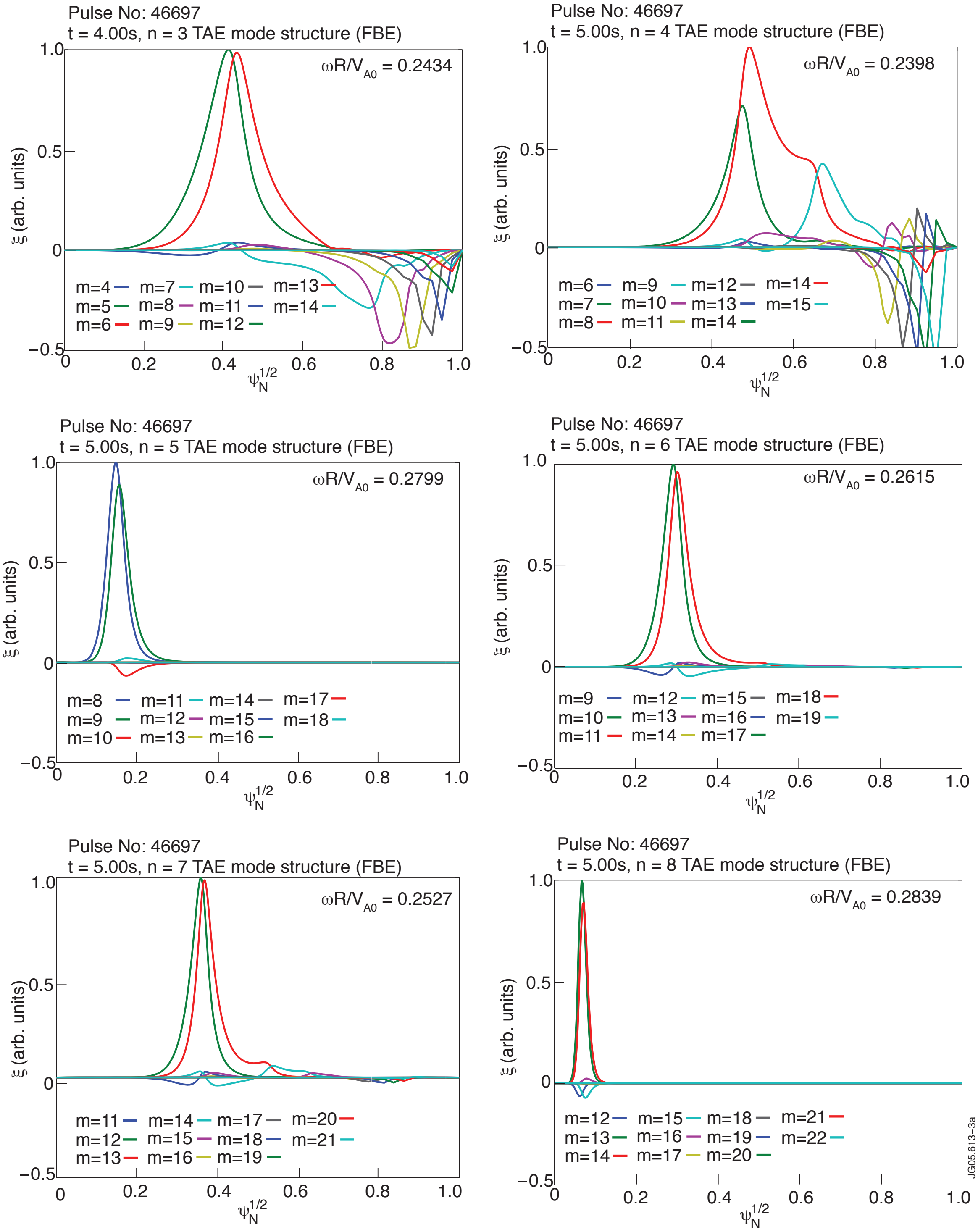

Figure 3(a): The n = 3 ÷ 8 TAE radial mode structure for the representative FBE case Pulse No: 46697.

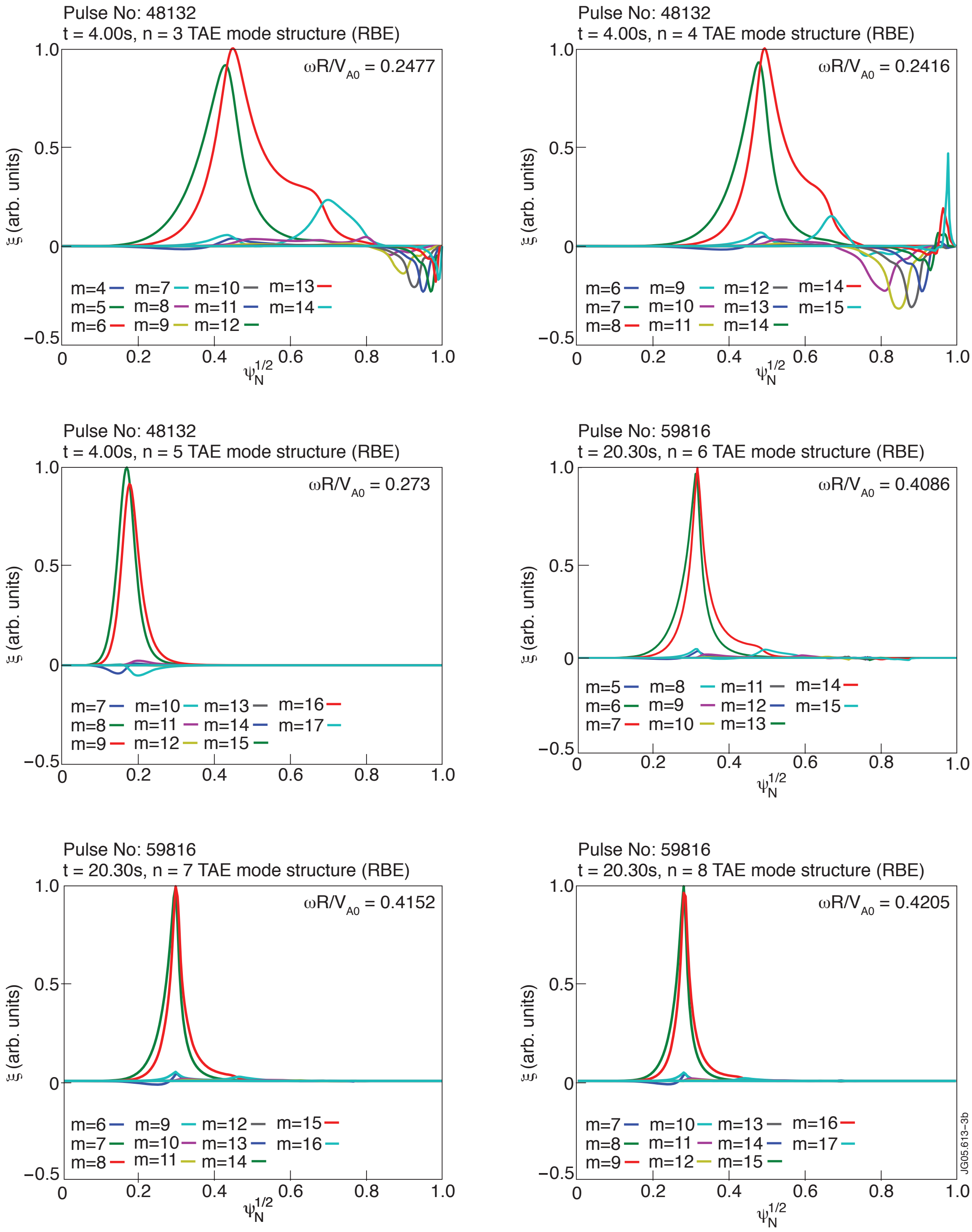

Figure 3(b): The $n = 3 \div 8$ TAE radial mode structure for the representative RBE cases Pulse No: 48132 ($|n| = 3 \div 5$) and Pulse No: 59816 ($|n| = 6 \div 8$).

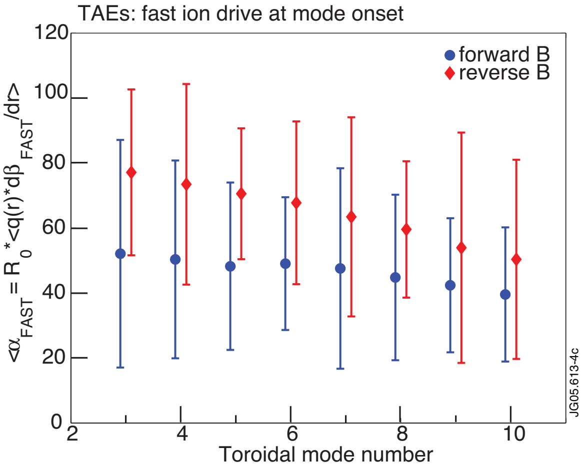

Figure 4: The TAE instability threshold as function of the magnetic field, hence ion ∇B-drift direction, for different toroidal mode numbers n's. Note that the computed fast ion drive $<\alpha_{FAST}>$ *is averaged over the radial mode structure so as to take into account possible differences in the TAE eigenfunctions for the forward and reverse B-field cases. The vertical bars indicate the spread in* $<\alpha_{FAST}>$*, which are related to variations in the background plasma parameters (density, temperature, plasma current and magnetic field, ICRF and NBI power) for the various discharges considered in our database.*