EUROFUSION WPJET1-CP(16) 15095

S Sharapov et al.

Energetic particle-driven Alfvn Eigenmodes in sawtoothing JET plasmas

Preprint of Paper to be submitted for publication in
Proceedings of 26th IAEA Fusion Energy Conference

Studies of Alfven Eigenmodes in the ITER Baseline Scenario, Sawtoothing JET Plasmas, and MAST Hydrogen-Deuterium Plasmas

S.E.Sharapov[1], M.Fitzgerald[1], C.McElvaney[1,2], V.G.Kiptily[1], H.J.Oliver[3], C.Perez von Thun[4], Yu.V.Yakovenko[5], B.N.Breizman[3], J.Ferreira[6], V.Goloborod'ko[4,5], T.Johnson[7], Y.Kazakov[8], M.Mantsinen[9,10], P.Rodrigues[6], F.Rimini[1], M.Salewski[11], M.Tsalas[12], and JET contributors*.

EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK
[1]CCFE, Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, UK
[2]University of York, York, Heslington YO10 5DD, UK
[3]Institute for Fusion Studies, University of Texas at Austin, Austin 78712, USA
[4]Institute for Theoretical Physics, University of Innsbruck, A-6020, Austria
[5]Institute for Nuclear Research, Ukraininan Academy of Sciences, Kiev, Ukraine
[6]Instituto de Plasmas e Fusão Nuclear, IST, Univ. de Lisboa, 1049-001 Lisboa, Portugal
[7]KTH Royal Institute of Technology, SE-100 44, Stockholm, Sweden
[8]LPP-ERM/KMS, TEC Partner, Brussels, Belgium
[9]Catalan Institution for Research and Advanced Studies, Barcelona, Spain
[10]Barcelona Supercomputing Center, Barcelona, Spain
[11]DTU Physics, DK-2800 Kgs Lyngby, Denmark
[12]FOM institute DIFFER, Nieuwegein, The Netherlands
*See the Appendix of F.Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia.

E-mail contact of main author: Sergei.Sharapov@ukaea.uk

Abstract. Modelling with the HAGIS code is performed to compute stability of α-particle-driven TAEs and redistribution of α-particles in the 15 MA baseline ITER scenario. For this modelling, 129 TAEs with n's from 1 to 35 were computed with the MISHKA code, and their damping was assessed with the CASTOR-K code. The self-consistent evolution of TAEs and α-particles results in TAE saturation amplitudes $dB_r/B_0=3\times10^{-4}$, with stochastic transport of α-particles localized in a narrow core region, and with α-particle redistribution beyond r/a=0.5 being minimal. Whilst these results are positive, their sensitivity to the sawtooth model used raises the issue of the hierarchy of various α-particle-driven Alfvén Eigenmodes (AEs) throughout the sawtooth cycle as well as the issue of re-distribution of α-particles by the sawtooth itself. Experiments on fusion products performed in JET sawtoothing plasmas give an indication of how AEs could vary throughout the sawtooth cycle in ITER. In these JET experiments, TAEs, EAEs, NAEs, and Alfvén Cascades were observed throughout the sawtooth cycle. Most often, core-localized TAEs inside the q=1 radius precede a sawtooth crash and cause a gradually increasing fast ion re-distribution/ losses seen in 2D γ-camera and scintillator. The sawtooth crash itself causes a strong short burst of lost fast ions followed by EAEs outside the q=1 radius, with EAE-induced losses. An inverse correlation between sawtooth crash times and sawtooth periods, $\tau_{crash}\propto(\tau_{saw})^{-\chi}$, $1\leq\chi\leq2$, is found using ECE diagnostics with ≤10 μs time resolution, facilitating the development of a model for sawtooth re-distribution of α-particles. In the field of energetic particle instabilities driven by velocity gradients, two recent developments are reported: i) a study of EAEs with $n=0$ observed in JET discharges, and ii) a study of compressional AEs (CAEs) in plasmas with mixed hydrogen isotopes. In the second case, deuterium-hydrogen plasmas with NBI-driven CAEs were obtained on MAST. A strong suppression effect of the D-H mixture was observed on CAEs in the ion-ion hybrid frequency range, $\omega_{BD}<\omega<\omega_{BH}$; a similar effect may be expected in D-T plasmas.

1. Introduction

Good confinement of fusion-born α-particles is essential for the success of ITER [1]. Possible resonant interaction of super-Alfvénic α-particles with weakly-damped Alfvén Eigenmodes (AEs) could affect strongly the confinement of α-particles if AEs are i) linearly unstable and ii) their saturation amplitudes are higher than the stochasticity threshold for α-particle orbits.

Also, if sawtooth oscillations take place in ITER, sawtooth-induced redistribution of α-particles may strongly affect the burning plasma performance. This paper presents recent modeling of α-driven TAEs in the ITER baseline scenario, studies of fast particle effects in sawtoothing JET plasmas, and of CAE excitation in MAST with two hydrogenic ion species.

2. Modelling of Alfvén Eigenmodes in the ITER Baseline Scenario

Modelling with the HAGIS code is performed to compute linear stability of α-particle-driven Toroidal Alfvén Eigenmodes (TAEs) and nonlinear TAE-induced redistribution of α-particles in the 15 MA baseline ITER scenario aiming at Q=10 [1-3]. For this modelling, a set of 129 TAEs with toroidal mode numbers in the range $n=1,\ldots,35$ was computed with the MISHKA code, and damping effects of the TAEs were assessed with the CASTOR-K code [2, 3]. The TAE growth rate has a maximum at around $n \approx 30$, and all TAEs computed could be divided into three distinctive groups: i) global TAEs consisting of many coupled poloidal harmonics and extended radially, ii) low-shear TAEs with frequencies at the bottom of the TAE-gap and consisting of two dominant harmonics with the same poloidal phase (even parity TAEs), and iii) low-shear TAEs with frequencies at the top of TAE-gap and consisting of two dominant harmonics with opposite poloidal phase (odd parity TAEs). Figure 1 shows the computed linear growth rates of all the modes. The even parity TAEs have the highest growth rates, but cannot cause any significant radial transport of α-particles as their radial mode widths are very narrow. On the other hand, global TAEs are radially extended, but have much lower growth rates. As a result of the self-consistent simultaneous interaction of all these different TAEs with α-particles in the ITER baseline scenario, TAE saturation amplitudes of $dB_r/B_0 = 3\times10^{-4}$ are found. For these amplitudes, stochastic transport of α-particles occurs in a narrow region containing core-localized TAEs, but α-particle loss and redistribution beyond $r/a \approx 0.5$ are minimal. It was estimated in [3] that significant stochasticity of α-particle orbits would only occur if the TAE amplitudes saturated at a level $\geq 1.5\times10^{-2}$, which is well above the level found in the simulation ($dB_r/B_0 = 3\times10^{-4}$). This factor ≥50 gives significant confidence in predicting that TAEs will not be important α-particle losses in the ITER baseline scenario.

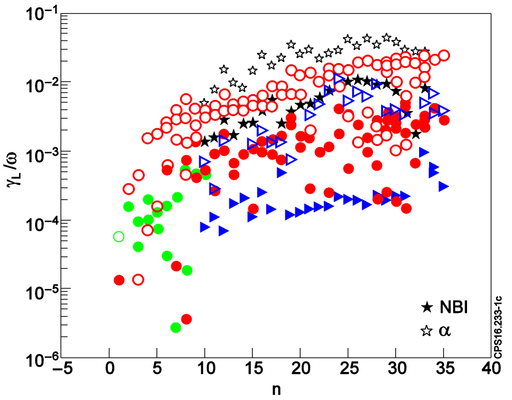

FIG.1 Normalized growth rates of TAEs driven by α-particles (empty markers) and NBI-produced D ions (solid markers). Global TAEs are marked with circles, even parity TAEs – with stars, and odd parity TAEs – with triangles. Green circles are stable TAEs.

In addition to α-particles, a population of deuterium (D) ions with energy up to ≈1 MeV produced by negative NBI in ITER was assessed with respect to TAE instability. Figure 1 shows that the normalized growth rates of TAEs caused by NBI-produced ions are about an order of magnitude smaller than those due to α-particles. These low growth rates are attributed to the use of off-axis geometry and power deposition profiles of NBI, in contrast to the centrally peaked α-particle profile [1].

Whilst these results are positive, their sensitivity [2] to low magnetic shear predicted by the sawtooth model raises the issue of whether the results are valid throughout the whole sawtooth cycle with a time-evolving q-profile.

3. Evolution of Alfvén Eigenmodes and fast ion losses during sawtooth cycle in JET

Experiments on fusion products performed on JET [4,5] have demonstrated that the evolution of fast ions and AEs in sawtoothing plasmas can be quite complex, especially if the effect of fast ion stabilization becomes important for sawtooth. Figure 2(a) shows time traces of the main JET parameters in a typical discharge #86762 (B_0=2.24 T, I_P=2.2 MA), where a monster sawtooth with a long period was caused by stabilization due to ICRH-accelerated ions. The sawtooth crash, which occurred at t=11.08 s, featured a very large, ≈50%, drop in the on-axis electron temperature, and very significant AE activity was observed before and after the crash. Namely, ≈ 0.3 s before the crash, TAEs localized inside the q=1 radius with toroidal mode numbers decreasing from n=9 to n=5 (so-called “tornado” modes) were detected, Fig.2(b). Fast D ions produced by combined ICRH and NBI heating were driving these TAEs, and the sequence of toroidal mode numbers was determined by the slow decrease of $q(0)$ passing through the TAE-relevant rational values. As shown in [6,7], an investigation of sawtooth stabilization by fast ions and re-distribution of such ions by high-frequency tornado modes, the tornado modes provoke crashes of sawteeth when they expel fast ions stabilizing the sawteeth from inside the q=1 surface to the region outside this surface. Such effects are rather well established for JET experiments, but remain to be investigated for ITER where stabilizing α-particle effects on sawteeth could play an important role.

In the JET discharge considered, the TAE activity stopped when the sawtooth crash expelled fast ions from the plasma centre to the plasma edge, detected using a scintillator probe (SP) [8] just outside the JET plasma. In contrast to losses gradually increasing during tornado mode activity, sawtooth crashes produce massive re-distribution of fast ions on a time scale of tens of µs. Because of the short time scale, both the diagnosis and the interpretation of fast ion re-distribution due to sawtooth crashes were difficult on JET. A recently improved ECE diagnostic with high time resolution, ≤10 µs, has made it possible to investigate sawtooth crashes in greater detail, see next Section.

Finally, Elliptical AEs were excited after the sawtooth crash in the JET discharge considered. These EAEs were not present before the crash, and they have both positive and negative toroidal mode numbers, including n=0 as Fig.2(c) shows. This implies that the EAEs are driven by free energy associated with velocity gradients in the fast ion distribution function, rather than its radial gradient, and that this bump-on-tail distribution emerged at the position of the EAE after the sawtooth crash only.

The n=0 EAE was computed with the MISHKA code as a mode with coupled poloidal harmonics m=±1 localized close to the plasma edge, r/a ≈0.8. The possibility of a bump-on-tail distribution resulting from expulsion of fast ions with large orbits during sawtooth crashes, as well as the possible use of n=0 EAEs for Alfvén spectroscopy of sawteeth [9] and for diagnosing fast ions in a similar way to the ICE approach [10], is under investigation and will be reported elsewhere.

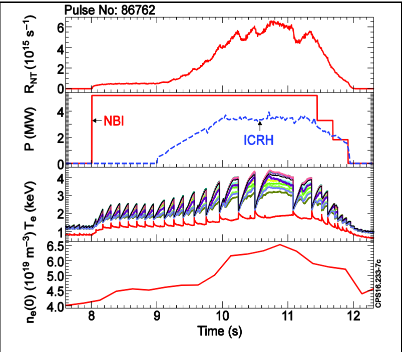

FIG.2(a) From top to bottom: Rate of DD fusion; Power of NBI and ICRH; T_e *measured with ECE; and* $n_e(0)$ *in discharge* #86762.

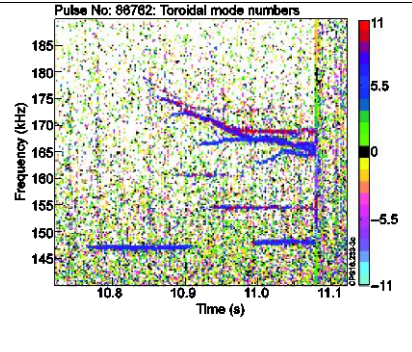

FIG.2(b) TAEs inside the $q=1$ *radius (tornado modes) with* $n=5$-9 *precede monster sawtooth crash at* $t=11.08$ *s.*

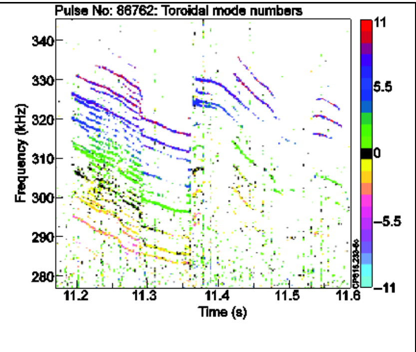

FIG.2(c) EAEs with $n=-3,..,+8$ *excited* ≈0.1 *s after sawtooth crash. No TAEs are seen at that time.*

A recently improved SP, which provides the best way of measuring fast ion losses in JET [8] can be used to measure the temporal evolution of fast ion losses in 16 specific bins with certain ranges of gyro-radius and pitch-angle. An example of such measurements throughout a sawtooth cycle is shown in Figure 3 for a JET experiment on three-ion ICRH involving ^{3}He as a minority species [11]. Figures 3(a),(b) show the temporal evolution of fast ion losses during TAE (tornado) mode activity, a sawtooth crash, and EAEs. Losses induced by EAEs comparable to losses due to the sawtooth are observed, caused by the proximity of EAEs to the plasma edge and SP.

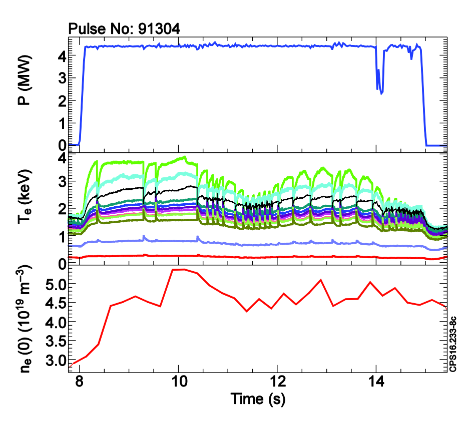

FIG.3(a) Power wave-forms of ICRH; T_e *measured with multi-channel ECE; and* $n_e(0)$ *in JET discharge* #91304.

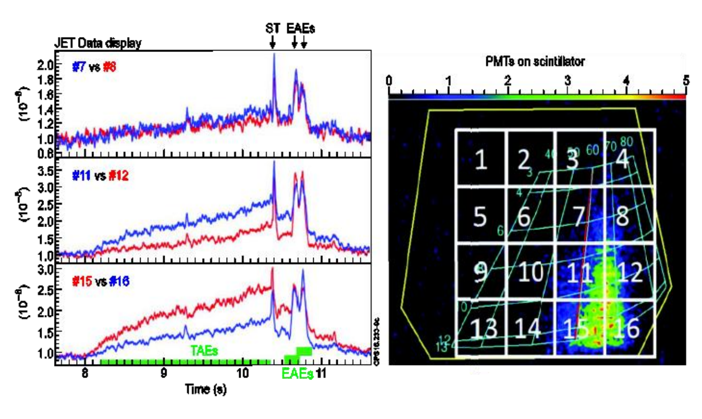

FIG.3(b) The scintillator plate measuring losses as function of gyro-radius and pitch shown with green grid (right); temporal evolution of losses to the bins covering pitch-angles of ICRH ions (left) in discharge #91304.

4. Investigation of Sawtooth Crash Times in JET Sawtooth Control Experiments

The theory presented in [12] on the redistribution of fast ions due to sawtooth crashes implies that the most affected trapped fast ions are those whose toroidal precession time, τ_{Dh}, is comparable to the sawtooth crash time, τ_{crash}:

$$\tau_{crash} \approx \tau_{Dh} = 2\pi/\omega_{Dh} \propto 1/E_h, \qquad (1)$$

where ω_{Dh} is the toroidal precession frequency of trapped fast ions, and E_h is fast ion energy. A statistically meaningful investigation of sawtooth crash times in the range of tens of μs recently became possible on JET through the use of multi-channel ECE diagnostics with time resolution ≤10 μs. Validation of the theory [12] and the development of a sawtooth redistribution model for fast ions with two essential parameters, $\tau_{Dh}/\ \tau_{crash}$ and $\tau_{SD}/\ \tau_{saw}$, are the aims of this study. Here, τ_{SD} is the slowing-down time of the fast ions, which determines time scale for establishing a steady-state distribution, and τ_{saw} is sawtooth period determined by the combination of transport, MHD, and fast ion stabilization effects. Measurements of fast ion re-distribution in the plasma core could be performed with neutron and γ-diagnostics, while losses could be measured with SP and Faraday cups [8]. For typical values of plasma current only fast ions with very high energy (in the MeV range) had orbits large enough to reach the plasma edge and the SP detector. The detection of fast ion losses with lower energy usually implies that the lost orbits originated from radii close to the plasma edge. The interpretation of such losses with the model proposed in [12] may require investigation of τ_{crash} as a function of radius, with ECE channels close to the relevant region.

For a data-set representing a variety of crash times, JET experimental data on sawtooth control [13] was considered. The aim of this experiment was to control sawtooth period and sawtooth crash amplitude with ICRH, in order to avoid the triggering of neoclassical tearing modes (NTMs). By considering sawteeth of different periods τ_{saw}, an important correlation was found between τ_{crash} and τ_{saw} shown in Figure 4. It was found, that longer period sawteeth not only have larger crash amplitude, but also their crash time is shorter, with the following relation for the discharges considered:

$$\tau_{crash} \propto 1/(\tau_{saw})^{\chi}, \text{ where } \chi=1\text{-}2.$$

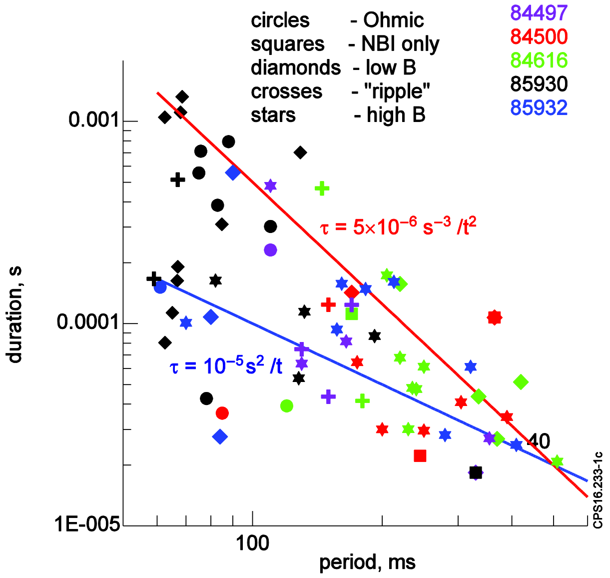

FIG.4 Statistical analysis of correlation between sawtooth crash times, τ_{crash}, and sawtooth periods, τ_{saw}, for several types of JET sawteeth. Red line corresponds to χ=2, blue – to χ=1.

Combining (1) and (2), one concludes that by controlling sawtooth period we can control to some extent the energy range of fast ions most significantly re-distributed by sawteeth. Taking into account the very high level of expertise in controlling sawtooth periods with ICRH and ECRH, this finding could become an interesting new development in the long-standing problem of fast ion re-distribution by sawteeth.

5. Compressional Alfvén Eigenmodes in D-H Plasmas on MAST

In the area of instabilities driven by velocity gradients of fast ions, in addition to the n=0 EAE, a study of CAEs was performed on MAST with deuterium-hydrogen mixtures and deuterium NBI. Due to the combination of low values of equilibrium magnetic fields, down to ≈ 0.3 T, and rather high plasma densities, $n_e(0) \approx (2\text{-}4)\times10^{19}$ m^{-3} achievable on MAST, both the Alfvén velocity and the ion cyclotron frequency in this machine are relatively low. This allows an extended investigation of i) Alfvénic instabilities (TAE, EAE, chirping modes), since even NBI-produced ions are super-Alfvénic, and ii) ion cyclotron instabilities driven by NBI-produced ions, since MAST magnetic coils are digitized up to 10 MHz sampling rate.

An in-depth investigation of CAEs driven by NBI on MAST has been carried out [14]. It is necessary, however, to investigate the excitation of such modes in plasmas consisting of two ion species with unequal cyclotron frequencies, in order to extrapolate the results towards deuterium-tritium (D-T) plasmas. The ion-ion hybrid frequency range is of particular importance as CAE damping and evolution in this frequency range are rather hard to predict. MAST discharges were performed with deuterium-hydrogen mixture varied from n_H/n_D=0 to n_H/n_D >2.57 by increasing hydrogen puff duration [15]. The concentration of hydrogen was measured with D_α/H_α spectroscopy at the plasma edge, while a neutron camera was used to measure depletion in the DD neutron rate to assess the H concentration in the plasma core [16]. In order to measure the entire frequency range relevant to the cyclotron instabilities (up to the hydrogen cyclotron frequency) with magnetic coils allowing measurements up to the Nyquist frequency of 5 MHz, magnetic fields of ≈ 0.3 – 0.38 T were used in MAST discharges at plasma current ≈600 kA. The on-axis values of plasma density and temperature at the time of CAE excitation were $n_e(0) \approx 2\times10^{19}$ m^{-3} and $T_e(0)\approx$800 eV. Plasma heating was provided by a single 2 MW NBI source with primary energy of 70-74 keV. Figure 5 shows CAEs excited in plasmas with increasing hydrogen concentration. The on-axis value of the D cyclotron frequency is about 2 MHz. It can be seen that NBI excites CAEs in a frequency range from ≈0.7 MHz to ≈3.5 MHz in a pure deuterium plasma on MAST, Fig.5(a). The amplitude of CAEs decreases and the frequency range shrinks significantly when significant amounts of hydrogen, n_H/n_D ≈0.3, are added to the plasma, Fig.5(b). CAEs are not excited at all in this frequency range when the hydrogen concentration becomes dominant, n_H/n_D ≈2.6, Fig.5(c). It is interesting to note, however, that CAEs of very high frequency, ≈4.3 MHz corresponding to the hydrogen cyclotron frequency, were observed in Fig.5(c) (investigated in more detail in [15]). Thus we conclude that CAE instability in the ion-ion hybrid frequency range is significantly suppressed, presumably due to increased mode damping, when concentrations of the ion species become comparable.

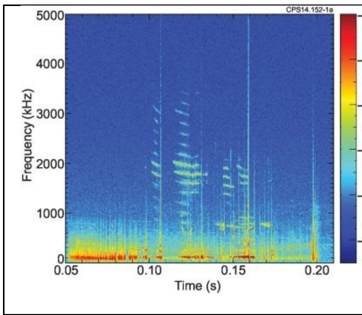

Fig.5(a) Magnetic spectrogram showing CAE excitation in pure D plasma on MAST, pulse #30457

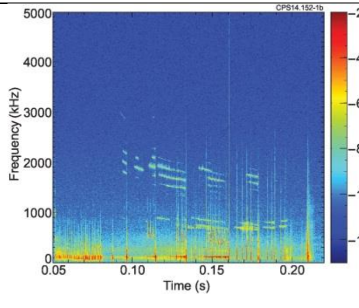

Fig.5(b) Magnetic spectrogram showing CAE excitation in plasma with n_H/n_D ≈0.3, pulse #30463

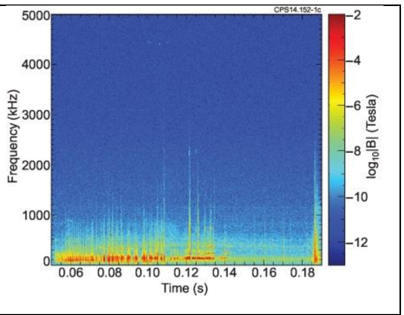

Fig.5(c) Magnetic spectrogram showing CAE excitation in plasma with n_H/n_D ≈2.6, pulse #30471

6. Summary and Conclusions

The ITER baseline scenario with 15 MA current aiming at Q=10 burning plasma, has been investigated for TAE instability and the possible effects of such modes on fusion-born alpha-particles and NBI ions in the MeV energy range. The spectral MISHKA code was used to identify possible TAEs in the ITER baseline equilibrium, and 129 modes were computed with n = 1,.., 35 of three different types: global TAEs, core localized TAEs of even parity, and core-localized TAEs of odd parity. Linear damping rates of all modes were assessed with the CASTOR-K model, and linear growth rates were computed with the HAGIS and CASTOR-K codes. It was found that core-localized TAEs have the highest net growth rates, but could only cause enhanced transport of α-particles within a rather narrow region, due to the small radial width of the modes. Global TAEs do have extended radial width, but their growth rates are found to be much lower than those of core-localized TAEs. As a result of self-consistent nonlinear HAGIS modeling with all 129 TAEs and the initial profile of α-particles expected in ITER [1], it was found that the saturation amplitude of TAEs is about 50 times lower than the orbit stochasticity threshold. No significant re-distribution of α-particles could therefore be expected for this ITER scenario.

TAEs driven by the MeV range super-Alfvénic NBI ions on ITER were also assessed. It was found that TAE growth rates caused by NBI are about order of magnitude lower than those due to α-particles. This rather weak NBI drive results from the off-axis NBI power deposition profile currently considered for ITER.

Experiments on fusion products performed on JET have demonstrated rather complex dynamics of AEs and fast ions in JET sawtoothing plasmas. Due to the essential coupling of fast ions and sawteeth via fast ion stabilization effects, TAE-induced transport of fast ions across the q=1 surface is found to facilitate sawtooth crashes. On the other hand, sawtooth crashes affect fast ions so significantly, that the TAE instability could stop, and EAE instability could occur closer to the plasma edge. Observations of EAEs with negative mode numbers and n=0 raises the issue of velocity gradients causing EAE drive, and indicates a possible opportunity for diagnosing sawtooth crash effects on fast ions via investigation of EAEs.

Preliminary study of sawtooth crash times on JET using ECE diagnostic with high time resolution showed that sawtooth crash times are inversely proportional to sawtooth periods. Due to the relation between sawtooth crash times and the energy spectrum of fast ions affected by sawteeth, the well-known techniques of sawtooth period control could be considered as tools for selectively affecting fast ions with certain energy re-distributed by sawteeth. This could be of particular interest for planned D-T experiments on JET as studies of these effects for isotropic α-particles are more ITER-relevant than those carried out using ICRH distribution functions with narrow ranges of pitch-angles.

Investigation of CAE instability in plasmas consisting of two ion species has shown significant suppression and disappearance of CAEs in the ion-ion hybrid frequency range when comparable concentrations of the ion species were used. This implies a similar effect for CAEs in D-T plasmas, which are essential for diagnosing fast ions via CAEs in ITER burning plasma.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053 and from the RCUK Energy Programme [grant number EP/I501045]. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] PINCHES, S.D., et al., "Energetic ions in ITER plasmas", Phys. of Plasmas **22** (2015) 021807.

[2] RODRIGUES, P., et al., "Sensitivity of alpha-particle-driven Alfvén eigenmodes to q-profile variation in ITER scenarios", Nucl. Fusion **56** (2016) 112006.

[3] FITZGERALD, M., et al., "Predictive nonlinear studies of TAE-induced alpha-particle transport in the Q=10 ITER baseline scenario", Nucl. Fusion **56** (2016) 112010.

[4] SHARAPOV, S.E., et al., "Fusion product studies via fast ion D-D and D-^{3}He fusion on JET", Nucl. Fusion **56** (2016) 112021.

[5] SCHNEIDER, M., et al., "Modelling of 3rd harmonic IC acceleration of D beams on JET", Nucl. Fusion **56** (2016) 112022.

[6] GIRARDO, J.-B., et al., "Stabilization of sawteeth with 3rd harmonic deuterium ICRF-accelerated beam in JET plasmas", Phys. of Plasmas **23** (2016) 012505.

[7] GASSNER, T., et al., "Deuterium beam acceleration with 3rd harmonic ion cyclotron resonance heating in Joint European Torus: Sawtooth stabilization and Alfvén eigenmodes", Phys. of Plasmas **19** (2012) 032115.

[8] KIPTILY, V.G., et al., "Recent progress in fast ion studies on JET", Nucl. Fusion **49** (2009) 065030.

[9] SHARAPOV, S.E., et al., "Development of Alfvén Spectroscopy in Advanced Scenarios on JET", Proc. of 21st IAEA FEC, Chengdu, China (2006), EX/P6-19, http://www-naweb.iaea.org/napc/physics/FEC/FEC2006/html/node370.htm#73948

[10] McCLEMENTS, K.G., "Ion Cyclotron Emission from JET D-T Plasmas", Phys. Rev. Lett. **82** (1999) pp 2099-2102.

[11] KAZAKOV, Ye.O., et al., "Fast ion generation and bulk plasma heating with three-ion ICRF scenarios", in: Radio Frequency Power in Plasmas, AIP Conf. Proc. 1689 (2015) 030008.

[12] KOLESNICHENKO, Ya.I, and YAKOVENKO, Yu.V., "Theory of fast ion transport during sawtooth crashes in tokamaks", Nucl. Fusion **36** (1996) pp 159-172.

[13] GRAVES, J.P., et al., "Sawtooth control in JET with ITER relevant low field side resonance ion cyclotron resonance heating and ITER-like wall", Plasma Phys. Control. Fusion **57** (2015) 014033.

[14] SHARAPOV, S.E., et al., "Bi-directional Alfvén cyclotron instabilities in the mega-amp spherical tokamak", Physics of Plasmas **21** (2014) 082501.

[15] OLIVER, H.J.C., et al., "Compressional Alfvén and ion–ion hybrid waves in tokamak plasmas with two ion species", Plasma Phys. Control. Fusion **56** (2014) 125017.

[16] KLIMEK, I., et al., "Determination of hydrogen/deuterium ratio with neutron measurements on MAST", Rev. Sci. Instr. **85** (2014) 11E109.