MHD spectroscopy of JET plasmas with pellets via Alfvén eigenmodes

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Abstract
Alfvén eigenmodes (AEs) are routinely seen in present-day tokamaks and stellarators with energetic particles and they represent an attractive form of MHD spectroscopy that provides valuable information on background plasma and on the energetic particles. Possible use of AEs is assessed for MHD spectroscopy of plasma with high-velocity pellet injection employed for fuelling the plasma core. Diagnostics of temporal evolution of the ablated pellets, as well as physics effects determining the diffusion/relaxation of the post pellet profile are of high importance for validating the pellet models and extrapolating them towards ITER. In this paper, JET discharges with ICRH-driven AEs and pellets launched from outboard and inboard tracks are considered. During the pellet injection, an increase in plasma density on a time scale \( \ll 50 \text{ ms} \) occurs, and several effects on AEs are observed: (1) frequency of the AEs throughout the pellet injection sweeps down by as much as \( \sim 30\% \), (2) the AE amplitudes increase during the AE frequency sweeping, and (3) spectrum of toroidal mode numbers of the AEs broadens significantly after the pellet injection. The effects observed are interpreted in terms of a rise in plasma density and an enhancement of the mode amplitude resulting from the resonance sweeping during the pellet injection.

Keywords: fusion, Alfven, MHD, tokamak, frequency sweeping, subcritical

(Some figures may appear in colour only in the online journal)
rate) is important for such scenarios, and the pellet size must be large enough to trigger an ELM. For the pellets made for the disruption mitigation [6–8], the size and number of pellets play a major role as these determine the efficiency of the radiation and avoidance of the runaway electron generation.

The wide range of the pellet parameters used in various machines for various purposes causes a spread in the characteristic time scales and pellet penetration distances at the pellet ablation. The aim of this paper is to investigate whether diagnosis of the pellet temporal evolution can be addressed by measuring Alfvén eigenmodes (AEs) that are seen routinely in present-day machines with auxiliary heating and may be naturally abundant in future burning plasmas with large populations of alpha-particles [9]. The AEs are usually numerous, they are easily detectable even at low amplitudes, and their eigenfrequencies are naturally determined by the mass density of the plasma affected by the pellets via

\[ \omega_{TAE} \approx \frac{V_A}{2qR_0}, \]  

where the Alfvén velocity \( V_A = \frac{B_0}{\sqrt{4\pi\rho}} \) (cm s\(^{-1}\)) depends on the mass density of plasma

\[ \rho \equiv \sum_i n_i M_i, \]  

which reads \( \rho = n_D M_D + n_T M_T \) in the most important case of D–T plasmas, with D density \( n_D \) and T density \( n_T \) satisfying \( n_D + n_T = n_e \), and neglecting plasma impurities and the He ash. In the case of plasmas with impurities, higher-Z pellets, and/or significant He ash, contributions of the impurities in the

\[ \text{Figure 1. Sketch of the poloidal cross-section of JET with the plasma contour at the last magnetic flux surface (separatrix shown in blue), the pellet injection tracks (H, V, L), the vertical lines of sight of the interferometer passing close to the magnetic axis marked with a cross (plasma core, C) and at the edge (E). Numbers 1 to 3 indicate the position of inboard Mirnov coils, while number 4 indicates the set of outboard toroidally separated Mirnov coils. The red lines without arrows show the pellet monitor view. Reproduced courtesy of IAEA. Figure from [13]. Copyright 2010 IAEA.} \]
mass density of plasma could become significant and should be assessed by, e.g. measuring $Z_{\text{eff}}$. However, such cases are not considered in this paper. During the injection of a pellet at high velocity into the plasma, successive surface layers of the pellet evaporate and are ionised to form a high-density plasmoid along the pellet’s path [1–3]. This 3D plasmoid deposited by the pellet is then spread at about the ion sound speed along the magnetic flux surface to provide a homogeneous density over the surface. Further $\nabla B$ drift and diffusion across the magnetic field cause the pellet perturbation to develop into a post-pellet density profile. In the presence of an unstable AE in the area affected by the pellet injection, the dynamics of

the mass plasma density could be monitored via the AE spectrum since from (1) and (2) one can see that the pellet-induced temporal evolution (increase) of the mass density results in a corresponding change in TAE frequency

$$\omega_{\text{TAE}}(t) \propto 1/\sqrt{\rho(t)}. \quad (3)$$

The use of AEs for MHD spectroscopy, i.e. for understanding properties of magnetically confined plasmas via the measurement of MHD perturbations (vertical lines) caused by the pellets A, B, C, and D (JET pulse #49044). Frequency corresponding to the centre of TAE-gap estimated via line-averaged electron density and $q \approx 1$ is shown with white trace.
the density evolution, it is of interest to investigate whether AEs can be used for obtaining information on the fast particle distribution in high density regions caused by the pellets.

2. Experimental setup

The pellet cases analysed in this paper include plasmas run on JET with the centrifugal pellet injector [4, 13] which was able to deliver D pellets with up to $3.8 \times 10^{21}$ atoms at speed in the range 150–300 m s$^{-1}$, along one of the three tracks available. The injection trajectories on the poloidal cross-section are shown in figure 1. Pellets are injected through one of the selected guiding tubes from the top (V), from the inboard (H), and from the outboard (L). Note that all three tracks are not crossing the magnetic axis and so aim at delivering pellets somewhat off-axis as shown in figure 1; this geometry caused a hollow density profile in many post-pellet JET plasmas.

Line-integrated electron density measurements with high time resolution are provided by an interferometer. The plasma density is integrated along two vertical lines of sight, one of which is close to the magnetic axis (the core line of sight, C), and the other close to the plasma edge at the low field side (E). In all cases considered, the efficiency of the pellet fuelling is determined by the integral of plasma density along the line-of-sight C passing through the magnetic axis at major radius $R_0$

$$\dot{n}_e \equiv \int n_e(R = R_0, Z) dZ \ (\text{m}^{-2}).$$

In addition, electron density profile could be measured by LIDAR diagnostic [14]. This has a low time resolution, however.

Alfvénic perturbations are measured by sets of Mirnov coils just outside the plasma surface. These coils are distributed along the toroidal and poloidal directions and measure perturbed poloidal magnetic field, $\delta B_p(t)/dt \sim \omega \delta B_p(t)$. Due to the rather high frequency of toroidal AEs (TAEs) and Elliptical AEs (EAEs), typically in the range of 150 kHz–450 kHz, the frequency factor in front of the perturbed $\delta B_p$ is high, so that perturbed magnetic fields could be measured at very low amplitudes down to $\delta B_p/B_0 \approx 10^{-8}$. The toroidal mode numbers $n$ of the AEs excited are deduced from the phase shift of magnetic perturbations measured by outboard coils with the same poloidal position, but separated toroidally.

In all JET cases considered here, AEs are excited by radial gradient of energetic H minority ($n_H/n_e \approx 2\%–5\%$) ions obtained in D plasmas with ion cyclotron resonance heating (ICRH) of high power, $P_{\text{ICRH}} > 4$ MW. The wave-particle resonances have the form

$$\Omega \equiv \omega - n_\parallel \omega_p - n_\perp \omega_p = 0, p = 0, \pm 1, \pm 2 \ldots$$
where \( \omega \) and \( n \) are the frequency and toroidal mode number of the AE, \( \omega_\perp = \omega_\perp(E, P_\perp, \Lambda) \) is toroidal precession frequency of the energetic ion drift orbit, and \( \omega_\parallel = \omega_\parallel(E, P_\parallel, \Lambda) \) is poloidal bounce-frequency (for trapped ions) or transit frequency (for passing ions). The orbit frequencies are best represented via the integrals of the ion motion: its energy \( E \), toroidal angular momentum \( P_\perp \), and the normalized magnetic moment \( \Lambda \equiv \mu B_\parallel/E = (V_{\text{perp}}/V_0)^2(B_\parallel/B) \), where \( \mu \) is the magnetic moment, and \( B_\parallel \) is the magnetic field on axis. For ICRH-driven AEs considered in this paper, the instability is driven by trapped energetic ions, and for the typical scenario with ICRH resonance at the magnetic axis (tips of the drift banana orbits are at the line \( R = R_0 \)), the normalized magnetic moment is \( \Lambda = 1 \).

At the nonlinear phase of instability, AEs driven with ICRH in JET have nearly constant saturated amplitudes and eigenfrequencies that follow in time the Alfvén scaling determined by the temporal evolution of the plasma mass density, \( \omega \propto B_0^{1/2} \) [15].

3. TAE evolution in JET discharges with high field side and low field side pellet injection

The efficiency of the pellet fuelling at the plasma core depends on whether the pellets are injected from the high field side or the low field side. The reason for this is that the opposite \( \nabla B \)-drifts of ions and electrons in the pellet cloud produces a local space charge, and hence a vertical electric field which crosses on the toroidal magnetic field to produce \( E \times B \) drifts which are directed towards or away from the magnetic axis for high field side and low field side injection geometry, respectively. Here, we investigate in more detail two discharges with AEs, one of which had the pellets injected from the track H, and the other from the track L [15, 16]. Figures 2 and 3 show the background parameters for the discharge with inboard pellet injection (H track) into plasmas with flat current top and \( q(0) \approx 1 \) (JET pulse \#49044 with \( B_T = 3.25 \) T, \( I_0 \leq 2.5 \) MA). The pellets are injected at the velocity of 154 m s\(^{-1} \). Figure 2 shows how the set of pellets keep plasma density increased throughout time, with the simultaneous drops in electron temperature after every pellet. The energy content of fast particles essential for excitation of AEs, exhibits a significant drop after first two pellets, and never recovers. Figure 3 shows that after first two pellets, \( n_\parallel \) nearly doubles and the \( n_\perp \)-profile becomes hollow. After every of the first four pellets (marked in figure 4 as A, B, C, and D), the increases in the line-integrated density are \( \delta n_\parallel \equiv \int \delta n_\parallel(R_0, Z) dZ = 5.44 \times 10^{19} \) m\(^{-2} \) (A), \( 4.86 \times 10^{19} \) m\(^{-2} \) (B), \( 4.51 \times 10^{19} \) m\(^{-2} \) (C), and \( 4.5 \times 10^{19} \) m\(^{-2} \) (D). Figure 2 (top) shows that every density increase after the pellet is followed by a decrease in particle confinement that relaxes the density rise down till next pellet is injected.

Figure 4 shows magnetic spectrogram with ICRH-driven AEs observed during the pellet injection. The modes seen before the first pellet A at frequency \(~220–250\) kHz are identified as TAEs, while the weak modes seen at \(~450\) kHz are EAEs. The activity of AEs becomes very weak (AE amplitudes are small) after \(~18\) s. This is in agreement with the drop in the fast ion energy content from \(~1.5\) MJ to \(<0.5\) MJ seen in figure 2, which is caused by the pellet-induced plasma cooling and plasma density increase, leading to a reduction in the fast ion slowing-down time.

In order to assess the position of TAEs, to which the pellet A penetrated, the JET equilibrium was reconstructed and modelling with the ICRH code PIOn and the ideal MHD spectral MISHKA code performed for the TAEs observed. Figure 5 shows the radial profiles of hydrogen minority fast ions computed with the PIOn code and averaged over the magnetic flux surfaces, before the pellets, and just after the second pellet B in JET pulse \#49044. In this discharge, the ICRH

![Figure 9](image1.png)

**Figure 9.** Outboard (L track) pellets in JET pulse \#49221 (\( B_T = 3.2 \) T, \( I_0^{\text{max}} = 2.5 \) MA). From top to bottom: \( \hat{n}_e(R_0) dZ \) (m\(^{-2} \)) (interferometer); \( T_e \) at different \( R \) from ECE; fast ion energy content \( W_{\text{out}} \) from PION code; ICRH (blue) and NBI (red) power waveforms.

![Figure 10](image2.png)

**Figure 10.** TAEs with \( n = 2–7 \) in JET \#49221. Times of injecting pellets A and B are shown. Reproduced from [12]. © IOP Publishing Ltd. All rights reserved.
power deposition was shifted somewhat to the high side of the magnetic field, with the ion cyclotron resonance layers from four RF antennae being at $R(\omega = \omega_{\text{BH}}) = 2.92 \text{ m}, 2.94 \text{ m}, 2.94 \text{ m}, \text{ and } 2.96 \text{ m}$, and the major radius of the magnetic axis being $R_0 = 3.0 \text{ m}$. Figure 6 shows the computed core-localised TAE with $n = 7$, radial position of which is within the drift orbits’ reach of the fast ions with their maximum gradient shown in figure 5. Thus we conclude that the pellet penetrated rather deep into the plasma core, $r/a \approx 0.3$, in order to have such a strong immediate effect on TAEs. In the case considered, the pellet does not trigger a sawtooth crash, so the condition of $q < 1$ remains valid throughout the pellet injection time and the position of the core-localised TAE remains nearly the same.

By zooming the magnetic spectrogram around time of the first pellet A, one can investigate in detail the phenomena seen in TAEs during the pellet injection. Figures 7 and 8 show the details of the amplitude and phase evolutions of TAEs just before, during, and after the pellet A injection.

Inspection of figures 7 and 8 shows that frequencies of TAEs dropped down by ~30% just after the pellet. From the relation $\omega_{\text{TAE}}(t) \propto 1/\sqrt{\rho(t)}$ one concludes that such a decrease in TAE frequency should correspond to the plasma density rise of $\approx 80\%$ (at $q$-profile fixed during the short time of the pellet interaction with the plasma). This significant increase in plasma density is consistent with interferometry measurement in figure 2 and in line with the LIDAR measurements in figure 3 made ~100 ms later. One concludes that the change in TAE frequency could be used for assessing the mass density increase at the TAE position during a pellet injection.

Next we note that the time scale of TAE frequency sweep after the pellet injection is $\tau_1 \sim 5$–8 ms, which is consistent with typical time scale of the pellet ablation [3–5], while the time of post-pellet TAE existence is $\tau_2 \sim 40$ ms consistent with the PION calculations shown in figure 2. The finite time of TAE observations after the pellet, in accordance with the PION modelling, is caused by the reduction in the fast ion drive at significantly decreased energy content of the fast ions. One concludes then that the AE measurements could also deliver information on the pellet temporal evolution and, to some extent, on the fast ion population at the position of TAE.

In addition, one could see that the pellet injection affected the frequency separation of TAEs, which is mostly caused by Doppler shift due to toroidal rotation of the plasma. In the case of figures 7 and 8, we observe a reduction in the toroidal rotation from ~8 kHz to ~5.6 kHz.

The effects described above could be understood within the existing modelling and be readily employed for the purposes of MHD spectroscopy. There are, however, two more effects visible in figures 7 and 8, which are new and hence require an additional study. First, some post-pellet TAEs were not observed before the pellet injection. Figure 8 shows that a broader spectrum of toroidal mode numbers exists in the
post-pellet plasma than in the pre-pellet. Second, figure 7 shows that amplitudes of TAEs after the pellet are somewhat higher than those before the pellet. Discussion of possible explanation of these effects is presented in the next Section.

Consider now a JET discharge similar to pulse \#49044, but with the pellet injected from the low field side. Figure 9 shows the parameters for the discharge with outboard pellet injection (L track) into plasmas with flat current top and \( q(0) \approx 1 \) (JET pulse \#49221 \( B_T = 3.2 \, \mathrm{T}, I_\phi \leq 2.5 \, \mathrm{MA} \)), and figure 10 shows the phase magnetic spectrogram of TAEs with toroidal mode numbers \( n = 2-7 \) seen at the time of the pellet injection. In this case, the pellets are injected at the velocity of \( 150 \, \mathrm{m \, s}^{-1} \). Again, one could see how the plasma density increases after every pellet, \( T_e \) drops, and the energy of fast particle content exhibits a drop down after first pellet.

After the pellets A and B, the increases in the line-integrated density are \( \delta n_e \equiv \int \delta n_e(R, Z) \, dZ = 8.36 \times 10^{18} \, \mathrm{m}^{-2} \) (A), \( 3.58 \times 10^{18} \, \mathrm{m}^{-2} \) (B).

Figure 10 shows magnetic spectrogram with ICRH-driven AEs observed during the pellet injection. The modes seen before the first pellet A at frequency \( \sim 205 \, \mathrm{kHz} \) are TAEs, and frequency of these TAEs sweeps down and up as the pellet cycle goes on.

From the observations of TAEs, one sees that TAE frequencies drop down by \( \sim 7.5\% \) only after the pellet A. From the relation \( \omega_{\text{TAE}}(t) \approx 1/\sqrt{\rho(t)} \) one concludes that such decrease in the frequency corresponds to the plasma mass density rise of \( \sim 15\% \) only. This value is much less than that achieved with the inboard pellet launch from H-track. Taking into account that the pellets were nearly similar in their size and velocity in both H-track and L-track cases, one concludes that plasma fuelling with pellets launched from the high field side is much more effective. This is in agreement with the expected effect of the \( \nabla B \) drift, and is also confirmed by the interferometer and LIDAR measurements available for these discharges.

Next, the time scale of TAE frequency sweep after the pellet injection is \( \tau_1 \sim 15 \, \mathrm{ms} \). This time is much longer than the sweeping rate timescale observed in the case with inboard launch of the pellets considered above. The reduction in the frequency separation of TAEs from \( \sim 10 \, \mathrm{kHz} \) to \( \sim 8 \, \mathrm{kHz} \) is also less significant in the L-track pellet launch than in the H-track launch indicating that the toroidal rotation of plasma is less affected by the pellet. The life-time of TAEs after pellet B is \( \tau_2 \sim 100 \, \mathrm{ms} \), which is in agreement with the PION code modelling.

Finally, in the case of the pellet launch from the low field side, the effects of the broadening of the spectrum of toroidal mode numbers of TAEs and TAE amplitude increase are less pronounced than in the case of the high field side pellet launch. Altogether, the comparison of TAE evolution in plasmas with pellets launched from the high field side and the low field side, shows a more significant density increase in a shorter time, in agreement with the expected effect of \( \nabla B \) drift on the plasma density at low field side injection is also in agreement with LIDAR measurements of the plasma density shown in figure 11. The PION modelling also shows a less significant decrease in fast ion energy content in this case, see figure 12.

4. Possible enhancement of wave-particle energy exchange due to resonance sweeping

We consider now whether some additional JET cases exist with a post-pellet TAE spectrum showing more unstable TAEs (in the number of modes and/or in their amplitudes) than the pre-pellet TAE spectrum, as was seen in the case of JET pulse \#49044 above. Figures 13 and 14 show another example of such kind. In JET pulse \#49032, the pellet injected at \( 18.208 \, \mathrm{s} \) from the H-track at velocity of \( \sim 180 \, \mathrm{m \, s}^{-1} \) caused a relatively small density increase of \( \delta n_e = 1.7 \times 10^{19} \, \mathrm{m}^{-2} \), but triggered many TAEs with toroidal mode numbers in the range of \( n = -6, -5, \ldots, +2 \). Note that the negative toroidal mode numbers of TAEs excited indicate that the modes are most likely driven by velocity gradients of the fast ion population (e.g. via bump-on-tail instability).

Another case showing only post-pellet TAEs in the absence of any pre-pellet TAEs is shown in figures 15 and 16. In this JET pulse \#49230 with low ICRH power insufficient to excite TAEs, pellets were injected at time intervals of \( \sim 27 \, \mathrm{ms} \) from the H-track at velocity of \( \sim 160 \, \mathrm{m \, s}^{-1} \). A significant spread was observed in the plasma density increase, e.g. the first two pellets shown in figure 15 caused \( \delta n_e = 3.8 \times 10^{18} \, \mathrm{m}^{-2} \) and \( 1.34 \times 10^{19} \, \mathrm{m}^{-2} \). However, every pellet injected was followed by excitation of a TAE, which was stable otherwise in the absence of the pellets, see figure 16. Due to low mode amplitudes, it was not possible to measure toroidal mode number of these post-pellet TAEs.

The search of effects, which could possibly explain more unstable TAEs in the post-pellet plasmas than in pre-pellet ones (seen in figures 8, 13 and 16) led to a hypothesis that the resonance sweeping naturally present during pellet injection and decrease in TAE frequency may enhance the wave-particle interaction as discussed in theory [17]. In this theory, the effect of resonance sweeping is shown to move the mode to the region of a fresh unperturbed distribution function of
energetic particles, which provide more free energy to the mode growth than the initial phase space region.

This theory states that (i) when the resonance for wave-particle interaction is varied adiabatically, the energy exchange is enhanced and higher amplitude of instability is achieved and (ii) this mechanism could even allow excitation of the instability in a system in which background dissipation suppresses linear instability. Both conclusions look compatible with the JET observations, but dedicated modelling is yet to be performed to validate the theory. Here, we only perform a direct comparison of the resonance maps before and after the pellet showing the phase space regions, in which fast trapped hydrogen ions resonate with a TAE mode.

The trapped energetic hydrogen ions accelerated with on-axis minority ion ICRH have a distribution function, which may be approximated in the form $f(E, \Lambda, P_{\phi}) = C f_0(E)$, where $f_0(E) \sim \exp(-E/T_{\text{tail}})$ is Strix energy distribution determined by the ‘tail’ temperature of the supra-thermal energetic ions, $f_0(\Lambda) \sim \exp(-(\Lambda - 1)^2/(\Delta \Lambda)^2)$ is the pitch-angle distribution highly peaked around $\Lambda = 1$ (typical width is $\Delta \Lambda \approx 1.5 \times 10^{-3}$), and $f_0(P_{\phi})$ is the radial energetic ion distribution (see, e.g. [18]). The most significant resonance between TAE and toroidal precession of the trapped energetic ions, $p = 0$ in equation (5), can be approximated by

$$\omega_{\text{TAE}} \approx V_\perp/(2qR_0) = \omega_{\text{p}} = q v^2 F(\Lambda)/(\omega_B r R_0),$$

$$F(\Lambda) = |E(k^2)/K(k^2) - 1/2|, \quad k^2 = 0.5(1 + (R_0/r)(1 - \Lambda)), \quad (6)$$

where $q$ is the safety factor at the resonance location, $E$ and $K$ are complete elliptic integrals of the first and second kind, respectively. During the density increase $\Delta n$ caused by the pellet, TAE frequency sweeps down correspondingly, $\Delta \omega_{\text{TAE}}/\omega_{\text{TAE}} \approx -0.5 \Delta n/n$, and the resonance condition (6) moves $\omega_{\text{p}}$ to another part of the phase space with a lower value. For a qualitative assessment whether the distribution function of energetic ions along the ‘swept’ trajectory of the resonance does not become empty and has still a free energy to excite the wave, we consider two resonance maps corresponding to the pre-pellet and post-pellet TAEs with frequencies 235 kHz and 160 kHz, correspondingly. First, we fix the corresponding to the pre-pellet and post-pellet TAEs with frequencies 235 kHz and 160 kHz, correspondingly. First, we fix the normalised magnetic momentum at $\Lambda = 1$ as all energetic particles produced by ICRH on-axis are close to this condition. This makes the resonance condition 2D as $\omega_{\text{p}} = \omega_{\text{TAE}} (E, P_{\phi}, \Lambda = 1)$. Also, for the trapped ions with banana tips ($\psi_0 = 0$) at $R = R_0$, the expression for toroidal angular momentum reduces to $P_{\phi} \propto -v_{\text{pol}}$, where $v_{\text{pol}}$ is the poloidal magnetic flux at the position of the turning point, which is a function of the vertical coordinate $Z$ only. This allows us to look at particle resonances in the reduced space $(E, Z)$. Trapped particles with starting positions distributed over the reduced space $(E, Z)$ were launched and followed by the HAGIS code [19], in the absence of TAEs, and frequencies of their toroidal precession orbits were calculated as functions of $E$ and $Z$. After
that, the resonance maps were generated as functions of $E$ and $Z$ (figures 17 and 18).

The white colour regions in these Figures correspond to the maximum of the plotted function $\log \left( \frac{1}{\Omega} \right)$, which correspond to the resonance condition (5). These resonance maps have nearly the same structure of the resonances across whole range of the frequencies swept in JET case #49044, from $\sim 235$ kHz to $\sim 160$ kHz if the trapped fast ions are core-localised, $Z < 0.6$ m (corresponding to $r/a \ll 0.4$, which agrees well with the mode and fast ion population localisations shown in figures 5 and 6). Furthermore, the structure of the resonances shows lines at an oblique angle to the energy axis. These resonance maps indicate then that at $Z < 0.6$ m, TAE frequency may sweep down all the way from $\sim 235$ kHz to $\sim 160$ kHz without losing the wave-particle resonance interaction as ions over a broad energy range, $200 \text{ keV} < E < 800 \text{ keV}$ could all resonate with such TAE.

5. Dynamics of ellipticity-induced AEs (EAEs) in JET discharges with pellets

Some JET discharges with ICRH do exhibit higher activity of higher-frequency EAEs than TAEs. This is the case of JET pulse #49220 shown in figures 19 and 20. The data suggest that the main reasons for EAE dominance in the spectrum are the pellet-induced sawtooth crashes. The sawtooth crashes can trigger EAEs by expelling energetic ions from the plasma core and generating a larger pressure gradient in the more external region of the profile where EAEs are localized. EAEs may be a good diagnostic tool for MHD spectroscopy, but usually the area occupied by ICRH-driven EAEs is further from the plasma core than that of TAEs, and so the information on the pellet dynamics obtained from EAEs corresponds to this larger plasma radius.

Figure 21 shows that EAEs driven by ICRH-accelerated ions, do behave in accordance with the plasma mass density cyclic evolution (increase in density just after the pellet with decrease that follows).
TAEs, the drop in frequency was immediate upon injection of the pellet. For EAEs, the decrease was usually immediate, but occasionally a delay of \( \approx 8 - 20 \) ms was measured before the EAE frequency responded to the pellet. This delay is significantly longer than the pellet transit time, \( \approx 5 - 6 \) ms, and the pellet ablation time, \( \approx 5 - 8 \) ms. Possible explanations for such time delays have yet to be found.

6. Pellet injection in JET discharges with high power off-axis ICRH and hollow energetic particle profiles

In some JET discharges with very high ICRH power, \( P_{\text{ICRH}} \leq 10 \) MW, massive AE activity was observed in the frequency ranges of TAE, EAE, and NAE (triangularity-induced AEIs). The very significant population of fast ions makes such plasmas a good test-bed for testing techniques of MHD spectroscopy, which could be suitable for burning plasmas. Figures 22 and 23 show an example of such JET discharge, pulse \#49777. In this discharge, ICRH was applied off-axis and hot ion pressure profile was hollow as PION results show in figure 23.
Figures 24 and 25 show the amplitude and the phase magnetic spectrograms for this discharge. The phase spectrogram shows that a mixture of both positive and negative toroidal mode numbers was observed, with somewhat larger number of modes with $n < 0$. This is expected for the hollow fast ion profile shown in figure 23.

7. Summary

In summary, pellets injected into plasmas cause significant changes in AEs, from which MHD spectroscopy could deliver the following information with high time resolution:

(i) Mass density increase (information on ion density and isotope mix).
(ii) Characteristic times of pellet evolution.
(iii) Characteristic times of fast ion slowing down after the pellet.
(iv) Evolution of plasma toroidal rotation evolution.

It was found that EAEs could also be used for MHD spectroscopy, but with some additional analysis required for the occasionally observed delays in EAE frequency sweep after the pellet injection. Two new effects associated with pellet injection into plasma with fast ions were observed: transient increase in AE amplitude and excitation of sub-critical post-pellet AEs. An explanation of these effects is likely to be found in the framework of the resonance sweeping theory enhancing the particle-to-wave power transfer.

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