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Prompt non-resonant neutral beam-ion loss induced by Alfvén eigenmodes in the DIII-D tokamak

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Abstract

Prompt neutral beam-ion loss due to non-resonant scattering caused by toroidicity-induced and reversed shear Alfvén eigenmodes (TAE/RSAEs) have been observed in DIII-D. The coherent losses are of full-energy beam ions born on unperturbed trapped orbits that would carry them close to a fast-ion loss detector (FILd) within one poloidal transit. However, in the presence of AEs, the particles are expelled from the plasma before completing their first poloidal orbits. The loss signals on FILd emerge within 100 μ s after the beam switch-on (which is the time scale of a single poloidal transit) and oscillate at mode frequencies. Time-resolved loss measurements show a linear dependence on the AE fluctuation amplitude and a radial ‘kick’ of ~ 10 cm by an $n = 2$ RSAE at $\delta B/B \leq 1 \times 10^{-3}$ can be directly inferred from the measurements. Full-orbit modelling of the fast-ion displacement caused by the AEs is in good quantitative agreement with the measurements. Direct interactions of the mode and the beam-ion orbit can account for a large fraction of fast-ion losses observed in such DIII-D discharges. The first orbit non-resonant loss mechanism may also contribute to enhanced localized losses in ITER and future reactors. A new diagnostic method of the radial displacement is inspired by these findings and can be used to study the interaction between fast ions and various MHD modes as well as three-dimensional fields.

(Some figures may appear in colour only in the online journal)

1. Introduction

In plasmas heated mainly by neutral beams, fast ions (also called energetic particles) are generated when the beam neutrals ionize. The density of fast ions (FIs) is much smaller than that of thermal particles. However, because of their high energies, they play an important role in plasma heating and a central role in reaching ignition in a fusion reactor. Ideally FIs and fusion products should be well-confined until their energy is transferred to the bulk plasma. However, they can be lost through prompt losses (also called first orbit losses). Prompt losses are losses of particles born on orbits that intersect the machine vessel wall before completing their first poloidal transit. The super-thermal particles can also be lost by perturbations of the background magnetic field directly, e.g. ripple losses [1, 2], test blanket modules (TBMs) [3, 4] and resonant magnetic perturbations (RMPs), [5] or through interactions with magnetohydrodynamic (MHD) modes [6]. FI

losses due to many different instabilities have been observed on DIII-D and many other machines; see, for example, [7–14]. Concentrated losses of FIs to the plasma-facing torus may cause appreciable sputtering and/or damage to the plasma-facing components [15]. Alfvén eigenmodes (AEs) can cause redistribution or losses of FIs in the plasma core through several mechanisms [15–17]. Flattening of FI profiles due to AEs has been observed [12, 18–20]. Understanding the FI transport and loss mechanisms and developing/validating theoretical models/codes in present experiments are crucial for the thermal design of plasma-facing surfaces and reliable predictions for ITER [21] and future devices.

One shortcoming of existing diagnostic techniques is that they cannot quantify the rate of transport caused by individual modes. A new loss mechanism has been discovered in DIII-D where toroidicity-induced Alfvén eigenmodes (TAEs) and reversed shear Alfvén eigenmodes (RSAEs) cause enhanced localized beam-ion losses as a result of interactions between

Figure 1. (a) Top and (b) poloidal cross-section views of the DIII-D tokamak. The eight neutral beam injectors are illustrated in (a). The 30L and 330L neutral beams have identical geometry except for 60° separation in toroidal location. The three vertical chords (V1, V2, V3) and the radial chord (R0) for the CO₂ interferometer are shown in (b) together with the 40 ECE radiometer channels which are viewing along a horizontal chord at the midplane. The FILD1 is located at a toroidal angle of 225° and ~45° below midplane while the FILD2 is located at 165° toroidally and near the midplane. The toroidal and poloidal projections of the first poloidal transit of a typical 30L beam ion that is born near the edge of circular shaped plasma are shown in (a) and (b) respectively. A typical oval-shaped plasma is also illustrated in (b). The gradient shading band in (b) is a cartoon of the beam footprint.

the FIs and the modes during a single poloidal transit [22]. The prompt loss mechanism affords a novel and direct way to determine the radial excursion of FIs imparted by an individual mode per poloidal pass. The radial displacement applies to not only these lost particles but also those particles which are not lost but scattered by the modes in the same fashion. The direct and quantitative measurement of the strength of AE–FI interaction per pass can be directly compared to model calculations and will advance our understanding of AE-induced FI transport.

In addition to their importance for fusion research, direct measurements of the deflection of energetic particles by Alfvén waves can contribute to our understanding of natural plasmas, for example, the scattering of energetic particles in the interstellar medium [23], the pitch-angle scattering of cosmic rays due to Alfvén waves [24], and the acceleration of energetic ions in solar flares [25].

The rest of this paper is organized as follows. Experimental observations (beyond those reported in [22]) of the prompt coherent losses for different neutral-beam sources, fast-ion loss detectors (FILDs), and plasma shapes are presented in section 2. Generally, TAEs cause prompt coherent losses more often than RSAEs. The explanations along with exceptional cases are also given in this section. Details of comprehensive simulations, including the calculated eigenmodes, the phase space of lost particles, and the method of background subtraction are described in section 3. Many observations are reproduced and details of the loss process are revealed from these simulations. In section 3, a method to experimentally infer the radial ‘kick’ (total radial displacement after one bounce orbit) is also described in detail. The unique ability for testing models is demonstrated through the quantitative agreement between the measured kick and the predicted kick from SPIRAL [26] simulation. In section 4, the work is summarized, followed by a discussion of its importance and implications.

2. Experimental observations

The primary auxiliary heating system on DIII-D consists of eight neutral-beam injectors, each injecting approximately 2.5 MW deuterium neutrals into the plasma. The beam injectors are grouped into four beamlines at 30°, 150°, 210° and 330° toroidally (figure 1(a)). The two beams at each toroidal location have different horizontal injection angles: one is more tangential while the other is more perpendicular and they can be referred as Left- and Right- beam according to their location inside the beamline housing, e.g. 330L and 330R. The sign convention of the plasma current (I_p) and toroidal magnetic field (B_T) in figure 1(a) is that counterclockwise is the positive direction. The $+I_p$ and $-B_T$ directions are the normal operation condition on DIII-D. All the neutral beams inject in the same direction as the plasma current except the 210° beams. The poloidal cross section of the DIII-D device is shown in figure 1(b) where the neutral-beam footprint (when injected on-axis) is illustrated as the grey shaded region. A few key diagnostics utilized for the work presented in this paper are also shown: the sightlines of three vertical chords and one radial chord of a CO₂ interferometer, the forty channels of electron cyclotron emission (ECE) radiometer and the two FILDs. FILD1 [27] is located at ~45° below the midplane and 225° toroidal angle, while FILD2 [28] is located near the midplane and 165° toroidal angle.

The FILD on DIII-D is a scintillator-based FILD. Ions enter into the detector through a collimating aperture and impinge on the scintillator. One branch of the illumination light is imaged onto a charge-coupled device (CCD) camera which resolves both pitch angle [$\alpha = \cos^{-1}(v_{\parallel}/v)$] and gyroradius (r_L) of the lost particles while the other branch is collected by a bundle of optical fibres and then coupled to photomultipliers (PMTs) that resolve losses with frequencies up to 500 kHz. Although all eight beams generate some fraction of prompt losses, the FILD can only detect ions in a limited range of phase

Figure 2. Time evolution of (a) plasma current and (b) $q_{\min}$, (c) line-integrated electron density, (d) 30L (red) and (e) 330L (blue) power, (h) smoothed FILD PMT signal, and (i) toroidal location after first poloidal transit of ions born near the centre of the 30L (red) and 330L (blue) beams where ϕ_{Tor} is the toroidal angle, going clockwise around the torus as viewed from above and 165° is where FILD2 locates; spectrograms of crosspower between vertical and radial CO_2 interferometer chords (f) and spectrogram of FILD data (g) in plasma discharge 146096.

space (e.g. $\alpha \sim [35^\circ\text{--}85^\circ] \pm 4^\circ$ and $r_L \sim [1.5\text{--}8] \pm 1.3$ cm for FILD2). In addition, FILD detection is also limited in configuration space, i.e. only collecting losses terminated at FILD location. Nevertheless, prompt losses from several neutral beams have been observed at FILD1 [29] and FILD2 under different plasma conditions.

FI-driven AEs are often observed with neutral-beam injection during the current ramping phase on DIII-D when the FI pressure is high. The primary experiment (shot 146096) discussed here has a total of ~ 4.5 MW deuterium neutral-beam power from combined co-injection of the 30L, 330L and 330R beams. The 30L and 330L beams have identical injection geometry, separated by 60° toroidally. Their tangency radius is $R_{\text{tan}} = 115$ cm. The 330R beam is more perpendicularly injected ($R_{\text{tan}} = 76$ cm) compared to the two other left beams.

Figure 2 shows time histories of key plasma parameters and loss measurements from the current ramping phase of the circular cross-section, reversed magnetic shear plasma (shot 146096). While the plasma current rises (figure 2(a)), the minimum safety factor ($q_{\min}$) decreases from 4.9 to 2.1 (figure 2(b)), the central density (n_e) measured by CO_2 interferometers [30] and Thomson scattering [31] increases from 1.2 to $2.0 \times 10^{19} \text{ m}^{-3}$ (figure 2(c)), the central electron temperature (T_e) measured by Thomson scattering and ECE [32] rises from 0.6 to 1.4 keV, the toroidal field (B_T) remains at ~ 2.1 T and the beam beta is comparable to the thermal beta according to TRANSP [33] analysis. Neutral beams are injected into the plasma starting from $t = 300$ ms. The 330R beam injects continuously while the 30L (figure 2(d)) and 330L (figure 2(e)) beams are alternatively injected every 10 ms so that the total power is constant. The continuous 330R beam together with the pulsed 30L and 330L beams drive a multitude of AEs with $1 \leq n \leq 5$, $m \leq 40$ (where n and m are the toroidal and poloidal mode numbers, respectively). As shown in the spectrogram of density fluctuations from interferometer signals (figure 2(f)), the dominant AEs are TAEs and RSAEs with frequency ranging from 50 to 220 kHz. The series of AEs with relatively constant frequencies are TAEs while the ones with up-sweeping frequencies are RSAEs. Many of these modes also appear on the FILD2 spectrogram (figure 2(g)),

indicating coherent beam-ion loss induced by AEs. The FILD1 did not detect any measurable losses because the location of FILD1 is not sensitive to losses from co-injected beams in circular-shaped plasmas in general.

Interestingly, the coherent losses are only observed during pulses of certain beam. The losses evolve with the q -profile and depend upon the beam source. Before 450 ms, FILD2 only detects coherent FI losses during the injection of the 30L beam; after 450 ms the losses coincide with injection of the 330L beam. This is surprising given the identical injection geometry for 30L and 330L, apart from the difference in the toroidal angle of injection. The 330R source has a more perpendicular injection angle and no losses on the FILD2 are observed from this beam in this discharge. The explanation for the source dependence of the observed coherent losses is that the modulated signals only occur when the unperturbed (no MHD activity) first orbit closely approaches the FILD location, thus allowing the AEs to deflect the ions into the FILD detector (see section 3). The unperturbed trapped orbits of 30L and 330L beam ions reach different toroidal angles after one poloidal bounce and only the ones that closely approach the 165° FILD2 location are deflected into the detector. Figure 1 shows the first bounce orbit of a 30L beam ion for the equilibrium at $t = 365$ ms. A deuterium atom that ionizes near the outer edge of the plasma closely approaches the FILD2 after one poloidal bounce. If this unperturbed orbit starts from 330L, it will reach a smaller toroidal angle and miss the FILD2.

The loss source switches from 30L to 330L and the maximum loss amplitude (figure 2(h)) evolves in time—first peaking at 365 ms, then peaking again at 550 ms. This temporal behaviour is due to the evolution of the plasma current. The coherent losses are observed during the current ramp-up phase of the discharge which means that the poloidal magnetic field is increasing and hence, the pitch angle of the injected particles born on trapped orbits near the plasma edge increases. The precession frequency (f_{pre}) of trapped particles decreases inversely with plasma current, $f_{\text{pre}} \propto I_p^{-1}$. Thus, when the plasma current increases, the point where the particle reaches its largest major radius moves in the toroidal field direction (clockwise direction in figure 1(a)). As the current

Figure 3. 30L neutral-beam voltage (10 μ s resolution) (black) and FILD PMT signal (red fast oscillating trace) during one 10 ms beam pulse. The loss signal (a) quickly ($\sim 100 \mu$ s) increases after the beam is switched on and (b) rapidly ($\sim 60 \mu$ s) decreases after the beam is turned off. The calculated typical poloidal transit time is about 80 μ s.

increases, the unperturbed orbits of 30L beam ions move away from the FILD2 while those of 330L beam ions move closer to the detector (figure 2(i)). The neutral beam deposition profile in $\phi - z$ cross-section is centrally peaked; that is, there are more beam ions (source of detected lost particles) born from the centre of the beamline than from the edge. The signal maxima at 365 and 550 ms occur because the effective toroidal displacement after one poloidal bounce matches the distance between the centre of the neutral beamline and the FILD2 at these times.

Examination of the FILD signal within a 10 ms beam pulse confirms that coherent losses occur on the first bounce orbit. The loss signals respond to beam modulation on the same time scale as a bounce-orbit period. The calculated time for a full-energy ion to complete one poloidal drift orbit shown in figure 1 is $\sim 80 \mu$ s. The time from the beam switch-on (10 μ s resolution) to the FILD2 PMT detecting a loss signal, and the time from the beam switch-off to the loss signal disappearing, is within 100 μ s (figure 3). The rise time of the loss signal is longer than the decay time, which is because it also includes the beam source response time and the travel time from the source to the plasma. Therefore, decay time is a more accurate measure of the lifetime (from born to lost) of detected particles. The loss signal begins to oscillate with the frequency of the AEs within one bounce time of the beam turn on. This means that the coherent losses commence before the beam ions have completed one poloidal transit. As resonant losses typically require interactions over multiple poloidal transits, this observation clearly indicates that the coherent loss is caused by a prompt non-resonant mechanism. However, these losses are different from what is generally referred to as prompt losses. Ordinary prompt losses are from ions born on unperturbed orbits that intersect the first wall, whereas the losses discussed in this paper are from ions deflected by AEs and have amplitudes strongly modulated at the mode frequencies.

The AE-induced prompt losses reported here are commonly observed during co-beam injection in DIII-D

plasmas over a range of plasma currents ($0.5 < I_p < 1$ MA) and a range of densities ($1.2 < n_e < 2.5 \times 10^{13} \text{ cm}^{-3}$). These losses are observed on the midplane FILD2 in circular-shaped and on both FILD1 and FILD2 in oval-shaped plasmas. Two example discharges are shown in figure 4. In these two oval-shaped plasmas, 30L and 330L beams are pulsed alternatively with each pulse on for 10 ms (figures 4(a) and (b)). A multitude of TAEs and RSAEs are driven unstable (figures 4(c) and (d)). The FILD2 detects AE-induced prompt losses from the 330L beam in discharge 146082 (figure 4(e)) because 330L beam ions come closer to the FILD2 after one poloidal bounce (figure 4(g)). The FILD1 detects AE-induced prompt losses from the 30L beam in discharge 142116 (figure 4(f)) because 30L beam ions approach closer to the FILD1 after one poloidal bounce (figure 4(h)).

Although the FILD detects particles at the vessel wall, at low plasma current the ions on large banana-width orbits first pass through the plasma core where the AE mode activity is localized. Therefore, information about modes which contribute to coherent losses but do not extend to the plasma edge, e.g. TAEs and RSAEs, may be acquired better (and with higher resolution) on the FILD detectors than on edge magnetic measurements.

Generally, TAEs cause prompt coherent losses more often than RSAEs. One reason is that RSAEs are more core-localized than TAEs. Therefore, RSAEs do not interact as often as TAEs with the type of banana orbits that pass close to FILDs, resulting in fewer measured losses. For example, three strong RSAEs (65, 70 and 88 kHz), three strong TAEs (76, 80 and 84 kHz) and three weak TAEs (90, 94 and 99 kHz) are observed on the ECE radiometer for the example shown in figures 5(a) and (b). However, the FILD only detects prompt coherent losses due to the six TAEs (figure 5(c)), despite the fact that the three higher frequency TAEs have much smaller mode amplitude compared to the three RSAEs. From the unperturbed banana orbit shown in figure 5(d), it can be seen that the particle only transverses into the plasma at $R \sim 203$ cm (the inner most radial location of the guiding centre (GC) on the

Figure 4. Time evolution of (a),(b) 30L (red) and 330L (blue) power, and (g),(h) toroidal location after first poloidal transit of ions born near the centre of the 30L (red) and 330L (blue) beams; spectrograms of (c) crosspower of CO₂ interferometer V1 and V2 chords and (d) crosspower of multiple ECE chords; spectrograms of (e) FILD2 and (f) FILD1 data in oval-shaped plasma discharge (left column) 146082 and (right column) 142116.

Figure 5. (a) Radial profile of three strong RSAEs (65, 70 and 88 kHz), three strong TAEs (76, 80 and 84 kHz) and three weak TAEs (90, 94 and 99 kHz) as measured by the ECE radiometer. (b) The six TAEs are clearly resolved from the crosspower of the two ECE channels near (dashed line in (a)) $R = 211$ cm. (c) The six peaks in the power spectrum of FILD2 signal correspond to the six TAEs in (b) with the coherence level to ECE data labelled near each peak. (d) A typical unperturbed orbit for this oval-shaped plasma (magnetic axis $R_0 = 169$ cm). The radial location of the GC orbit across the midplane is indicated in (a) as a solid line (orange, labelled as $R_{\min}$ (GC)).

midplane). The RSAEs are too far inside to affect the particle orbits while all the six TAEs interact with the particles.

Figure 6 shows that direct interaction of the particle with the mode is generally required for a measurable kick and resultant loss. Here the distance between the radial peak of the eigenfunction (measured by ECE) and the minimum radius of the unperturbed GC orbit on the midplane serves as a measure of whether the orbit and the mode intersect. Figure 6 shows strong asymmetry because the particle orbit is not a function of flux surface. Measurable coherent fluctuations only occur when the eigenfunction maximum extends beyond the

minimum major radius of the orbit. Of course, the magnitude of the FILD oscillation depends on many other factors that are not considered here, such as the gyroradius (about 4–5 cm for these orbits), the integrated path of particle–wave interaction and the mode structure. Modes that do not cause losses (data points on the negative x -axis) are mostly RSAEs and core-localized TAEs.

However, RSAE-driven prompt losses are seen in some situations. At very low plasma current, the banana width is large enough that the orbits intersect with RSAEs; an example is shown in section 3. At higher current, RSAEs with strong

Figure 6. FILD oscillation amplitude (normalized to the peak ECE amplitude) versus orbit position for 32 different cases. The abscissa is the distance between the major radius of the peak ECE signal and the minimum major radius of the GC orbit at the midplane. Negative values on the x -axis mean that the mode is located at a smaller major radius at midplane than the orbit.

mode amplitude and wide spatial structures extend outward to intersect (figure 7). In discharge 146076, many RSAEs and TAEs are driven unstable. FILD2 detects losses from TAEs and from one RSAE (during 430–440 ms, 65–75 kHz). Generally, the mode numbers are difficult to be resolved for these highly core-localized, fast chirping AEs from edge magnetic measurements. But this RSAE has such broad spatial structure (figure 7(c)) and strong mode amplitude that its toroidal mode number ($n = 2$) is well resolved. The mode extends beyond $R = 210$ cm, leading to the observed direct losses.

3. Simulations

Comprehensive simulations have been performed using a variety of experimental inputs to explore the loss mechanism. Equilibrium profiles of electron density, electron temperature and the density, temperature and toroidal rotation of carbon ions measured by charge-exchange recombination (CER) [34] are fitted using plasma equilibria reconstructed with EFIT [35] and constrained by motional Stark effect (MSE) measurements [36]. The phase space of the detected FI losses is calculated using a revised version of the NLSDETSIM code [37]. The expected beam-ion deposition profiles are calculated using the NUBEAM [38, 39] module of TRANSP and outside the last closed flux surface (LCFS), they are calculated using an IDL code which employs similar approach as that in NUBEAM [40]. The ideal MHD eigenmodes are calculated using NOVA [41]. The eigenmodes from NOVA are matched observations and the mode amplitudes are obtained by scaling the calculated temperature fluctuations to the measured ones as shown in figure 8 [42]. Figure 8 shows both the measured and NOVA predicted radial profiles of the temperature perturbation due to a core-localized $n = 2$, $m = 7$ RSAE at 117 kHz in the primary discharge 146096. The interaction of the particle with the mode is calculated using the full-particle-orbit-following SPIRAL code [26]. SPIRAL uses inputs such as the calculated birth profile and AE structure from NOVA superimposed on the reconstructed EFIT equilibrium. The SPIRAL code computes Lorentz orbits with a realistic wall model. The slowing down

and Coulomb scattering processes are included in the SPIRAL simulations presented here, although they have a minor effect on the prompt loss time scale.

A camera frame of the detected FI losses on the FILD2 scintillator at $t = 368.75$ ms when the 30L is on in the plasma of figure 2 is shown in figure 9(a), overlaid with the calculated mapping grid. The contour plot of the camera frame region of interest is transferred to standard energy and pitch ($v_{||}/v$) space (figure 9(c)). The next camera frame at $t = 375$ ms during one 330L beam pulse is shown in figure 9(b) where no loss is detected. However, later in the discharge losses are clearly detected during 330L beam pulses, for example at $t = 550$ ms (figure 9(d)). The losses centred at gyroradius $r_L \approx 3.8$ cm and pitch angle $\alpha \approx 57.5^\circ$ or pitch ~ 0.54 (figure 9(a)/9(c)) coincides (within the FILD2 resolution range of ($\Delta\alpha \sim 4^\circ$, $\Delta r_L \sim 1.3$ cm)) with the prompt loss region of phase space for full energy trapped ions from the 30L/330L beams in MHD-free plasmas.

Full-orbit-following Monte Carlo SPIRAL simulations have been carried out to study AE–FI interactions. Normally, SPIRAL simulations start with the beam deposition profile and follow particles with full injection energy to see if they will hit the FILD detectors. However, this approach is impractical for the case discussed here because the fraction of particles that reach the FILDs after interactions with the modes is very small. To improve the statistics, reverse simulations are employed instead, where particles are introduced over the detected pitch range from the FILD2 location at uniform rate for one AE cycle and traced backward in time with AE fields present to the injection planes of the 30L and 330L beams. In this way, only FILD2 hits are obtained. The simulation results for 30L and 330L beams using the plasma equilibrium profile at the same time as that in figure 9(a) with the presence of an $n = 2$, 117 kHz RSAE are shown in figures 10(a) and (b), respectively. In the SPIRAL simulations, $\delta n_{\text{peak}}/n \approx 1\%$ due to the AE is applied which corresponds to $\delta B_{\text{peak}}/B \approx 10^{-3}$. The $\delta n/n$ value is based on the measured $\delta T_e/T_e$ value via the equation of state and the plasma displacement [42]. The comparison of the back-tracked particles at the beam injection plane with the beam footprint (pitch and height) from NUBEAM shows good overlap for the 30L beam (figure 10(a)) but no overlap for the 330L beam (figure 10(b)).

SPIRAL simulations also find that the observed losses are dominated by trapped ions being scattered by AEs onto lost orbits, which intersect the FILD2. To illustrate this, the poloidal projection of the orbit of a typical single particle (from figure 10(a)) that intersects the AE and then is lost to the FILD2 is shown in figure 11. A neutral-beam particle ionizes near the plasma edge on a banana orbit (magenta curve) such that it will come close to the FILD2 after one poloidal bounce if there is no MHD activity. When this ion traverses the plasma core in the presence of the RSAE, it interacts with the mode and its orbit (yellow curve) starts to deviate from the unperturbed orbit. The turning point (lower banana tip) migrates inward about 10 cm compared to the unperturbed orbit, thereby moving the ion radially outward at the low-field side (LFS) midplane into the FILD2. Depending upon the phase of the mode, the radial excursion can be inward or outward; small or large (or zero). At a phase different from the one shown in figure 11, the radial excursion is different and the particle will miss the FILD2. As

Figure 7. Time evolution of spectrograms of (a) crosspower of CO₂ interferometer R0 and V2 chords and (b) FILD2 data in discharge 146076. The loss with up-sweeping frequency near 70 kHz at 435.5 ms is due to a RSAE (circled in (a) and (b)) with structure shown in (c) measured by ECE radiometer (also shown in (a) at the same frequency and time). The orange line in (c) represents the minimum major radius of the GC orbit at the midplane (labelled as $R_{\min}(\text{GC})$) (magnetic axis $R_0 = 170$ cm).

Figure 8. Measured by ECE radiometer (squares) and NOVA code predicted (solid line) temperature perturbation for $n = 2$ RSAE at $t = 365$ ms for discharge 146096. Predicted eigenmode amplitude obtained by least-squares fit to the ECE data. Typical error in ECE measurements (calculated based on the noise floor) and representative ECE channel width are shown.

the mode propagates toroidally, the radial excursion oscillates in and out, leading to coherent oscillating losses from the vantage point of the FILD. Consistent with the experiments, simulated losses appear within one poloidal transit time and are modulated at the mode frequency shown in figure 12. The majority of these lost ions are knocked out from the plasma before completing their first orbit. Only a very small fraction ($<2\%$) of these lost particles is pushed out on later orbits (mostly on the second and third poloidal transits). Simulation reveals that the change in pitch due to the mode is dominant while the change in energy is generally small. For example, for a mode at $\delta B_{\text{peak}}/B \sim 10^{-3}$, the change in pitch can be as big as 15% while the change in energy is only 1–2%.

This process can also be viewed in the space described by the constants of motion of the unperturbed orbit. Figure 13 shows the orbit topology [43] in terms of the magnetic moment μ ($\mu = mv_{\perp}^2/2B$) and canonical momentum P_{ϕ} [$P_{\phi} = q\psi_{\text{pol}} - mv_{\parallel}(B_{\text{Tor}}/B)R$] calculated for 80.4 keV 30L beam

ions using the plasma equilibrium of figure 12, where m is the mass, $v_{\perp}$ and $v_{\parallel}$ are the velocity perpendicular and parallel to the magnetic field respectively, B is the local magnetic field and B_{Tor} is the toroidal component, q is the charge, Ψ_{pol} is the poloidal magnetic flux and R is the major radius. A wave can move an ion across the topological boundary between different types of orbits and cause radial transport. Particles that move towards the left on the P_{ϕ} axis travel outward from the magnetic axis. The 30L beam ion density profile calculated using TRANSP/NUBEAM is plotted in figure 13 along with the range of orbits of full-energy beam ions that could terminate at the FILD with experimentally observed pitch angle. The equivalent orbits at the start and end points of the example perturbed orbit shown in figure 11 are also marked. It readily illustrates that the confined trapped beam ion is pushed across the loss boundary by the mode into the FILD. At another phase, e.g. 180° away from the phase shown in figure 12, the particle is pushed in the opposite direction and remains confined.

The dependence of these prompt coherent losses (ΔF) on the AE amplitude has been studied to learn more about the loss mechanism. In practice, the mode amplitude is derived from electron temperature fluctuations ($\delta T_e/T_e$) measured by ECE radiometer and ΔF is obtained from the fast Fourier transform (FFT) of the FILD signal tracking the frequencies of the same mode. Noise subtraction is employed for both ECE and FILD signals; an example is given in figure 14. The dominant noise source in the ECE measurements is thermal noise while the noise in the FILD signal is dominated by plasma stray light.

It has been found that the loss scales roughly linearly with the mode amplitude, signalling it is a non-diffusive or ballistic loss process. The slope is different for different modes, as expected since it depends on many factors, such as the mode structure, the mode location and frequency. For example, the TAE at 94 kHz has weaker mode amplitude than the TAEs at 76 kHz and 84 kHz shown in figure 5; however, the amplitudes of their induced losses are comparable. Two

Figure 9. Camera frame of the FILD2 scintillator at (a) $t = 368.75$ ms when 30L (80.4 keV) is on, (b) $t = 375$ ms and (d) $t = 550$ ms when 330L (74.5 keV) is on with calculated mapping grid overlaid. The loss region of interest shown in (a) is transferred to normal pitch and energy coordinates in (c).

Figure 10. Comparison of (colour contour) back-tracked particles (all trapped particles) from reverse full-orbit Monte Carlo SPIRAL simulations and (line contour, in linear scale) beam birth profiles of (a) 30L and (b) 330L calculated by TRANSP/NUBEAM using equilibrium at $t = 365$ ms of discharge 146096 with an $n = 2$, 117 kHz RSAE present.

additional examples are shown in figure 15 where the coherent loss amplitudes are plotted against the fluctuating temperatures due to a co-existing RSAE and TAE during 320 to 330 ms from the plasma of figure 2. Both modes peak near the $q = 3.5$ surface; the RSAE has mode number of $n = 2$ and frequency of 52 kHz and the TAE has $n = 5$ and frequency of 120 kHz. At the same mode amplitude, the TAE causes more FI losses. Although the rough linear relation between the loss intensity and mode amplitude is observed for many modes, deviations from the linearity are observed for some modes too, e.g. the TAE in figure 15. This is thought to be caused by non-linear interactions between the particles and multiple waves, which is subject of a separate publication.

The general linear dependence arises because the deflection of the particle is proportional to the mode amplitude; thus, with different mode amplitudes, particles from different locations are pushed into the FILD. For example, at very low mode amplitude, only the relatively few ions born in the scrape-off layer (SOL) are lost. At large mode amplitude, particles from further inside the plasma are lost so that more particles are detected at the FILD. Because of this relationship, the prompt loss measurements allow one to measure the radial kick caused by individual AE during a single transit.

Because of the existence of unperturbed orbits that ‘connect’ the FILD to the portion of phase space populated by injected neutrals, some prompt losses occur even in the

Figure 11. (a) Orbits calculated using the SPIRAL code: GC (magenta) orbit of a 30L beam ion (ionizes at pink square) in the absence of a mode; full (black) and GC (yellow) orbit lost to FILD (red triangle) in the presence of (colour contour) an $n = 2$, 117 kHz RSAE ($\delta B_{\text{peak}}/B \sim 10^{-3}$). A magnified view of the perturbed and unperturbed GC orbits near the mode is shown in (b).

Figure 12. Loss signal modulated at the mode frequency obtained from a SPIRAL simulation with an 95 kHz RSAE present.

absence of a mode. The amplitude of these unperturbed losses at the FILD ($\bar{F}$) is proportional to the ionization rate where the orbit intersects the beam footprint. In the linear region, an AE at a higher (lower) amplitude gives the ions a larger (smaller) radial kick and effectively moves the birth location up (down) the ionization gradient, producing more (less) loss as illustrated in figure 16. Hence, the magnitude of the signal fluctuation (ΔF) is proportional to the ionization gradient and to the radial kick (ζ) [22],

$$\Delta F / \bar{F} \approx \zeta / L_i \quad \text{or} \quad \zeta \approx (\Delta F / \bar{F}) L_i, \quad (1)$$

where L_i is the beam ionization scale length at the point where the unperturbed prompt orbit ionizes. (More comprehensive analytical expansion of equation (1) is included in the appendix.) To use equation (1) to determine the radial kick ζ , one must infer ΔF , $\bar{F}$ and L_i from the data.

Figure 13. Map of orbit topology of FIs in magnetic moment (μ) and canonical angular momentum (P_ϕ) space: lost, trapped, counter-passing, co-passing, stagnation, and potato (intersection between trapped and co-passing). The 30L birth profile (black dots) is also shown. The orbits in the purple rectangular region reach the FILD within the detected pitch range at full energy. The starting (pink square) and ending (red triangle) points of the perturbed orbit shown in figure 8 are marked. B_0 is the on-axis magnetic field; $E = 80.4$ keV is the ion energy; and Ψ_{wall} is the poloidal flux at the wall.

The loss fluctuating at the mode frequency ΔF is readily determined from the FFT of the scintillator signal (figure 14). After subtraction of the noise floor, the integral over the peak in the amplitude spectrum yields ΔF (rms value is used for all the calculations).

The ionization location of the unperturbed prompt orbits is calculated using synthetic modelling [29], which solves the Lorentz equation with given ion energy, pitch angle and plasma magnetic equilibrium and traces the ion orbit from

Figure 14. Power spectra of (a) FILD signal (sampled at 1 MHz, NFFT= 2048, ‘hanning’ window) and (b) ECE electron temperature fluctuations measurement (sampled at 500 kHz, NFFT= 1024, ‘hanning’ window) at $t = 328.3$ ms in discharge 146096. The peak between the vertical dotted lines is the mode of interest ($n = 2$ RSAE). The noise floor in both signals (dashed line) are removed in further analysis. The coherence between FILD signal and ECE signal is shown in (c).

Figure 15. Fluctuating FILD loss amplitude ΔF versus the mode amplitudes for (squares) an $n = 2$, 52 kHz RSAE and (triangles) an $n = 5$, 120 kHz TAE co-existing near the $q \sim 3.5$ surface between 325 and 330 ms in discharge 146096. Typical error bars (calculated based on the noise floor) are shown.

the FILD back into the plasma. The intersection of the ion orbit with the corresponding beam footprint and correct pitch is the ionization location. The beam ionization scale length is assumed to equal the electron density scale length (L_n). The electron density is measured by Thomson scattering and sometimes by profile reflectometry [44]. Although the beam ionization rate depends on T_e and the effective ion charge (Z_{eff}) as well as on the density, the T_e and Z_{eff} dependencies are weaker than the linear dependence on n_e . Consequently, the density scale length is a good representative of the ionization rate. Figure 17 compares the edge beam-ion deposition profile calculated from NUBEAM with the edge density profile fitted from Thomson scattering measurements. Inside the plasma, there is very good agreement between these two scale lengths. In the SOL (not shown), the density is low and few ions are born. An exponential extrapolation is usually utilized in this

Figure 16. Cartoon to show how radial kick can be resolved from the relation between mode amplitude, ionization rate and FILD loss amplitude.

Figure 17. Calculated edge ionization rate (black line) and fitted edge density profile (red solid line with error band shown by dashed lines) from Thomson scattering measurements at $t = 325$ ms in discharge 146096.

region. Because the edge density fluctuation ($\tilde{n}/n$) associated with AE activities is less than 0.05%, AEs have negligible effects on the edge ionization profile.

Determination of the dc loss signal $\bar{F}$ is complicated by contributions to the signal from other modes. The scintillator signal contains contributions from stray light, from normal prompt losses, and from prompt losses induced by the various AEs. The signal produced by an individual ion is unipolar. This means that, when many different modes are causing

Figure 18. Signals generated using the synthetic model (red) to match many features of the measured FILD signal (black). (a), (b) are in the time domains and (c) is in the frequency domain.

losses, the apparent dc baseline can rise, leading to an overestimate of the prompt losses that would occur in the absence of instability. To guide interpretation of the signal, we construct a model signal with the following elements.

- Gaussian noise, determined from the standard deviation of the signal before the beam turns on.
- Unipolar loss signals that contain several harmonics in addition to the fundamental.
- Several modes with different frequencies and amplitudes. Some of the frequencies sweep in time (representing RSAEs). All of the amplitudes vary in time with a frequency of ~ 1 kHz.
- A dc signal, representing normal prompt losses.

Figure 18 compares actual data with synthetic signals in the time and frequency domains. The random noise in the model is needed to match the noise floor of the actual FFT. The unipolar model improves the similarity in the time domain. The amplitude modulation in the model is essential to match the observed spectral broadening. The dc signal elevates the baseline when the beam turns on, as observed experimentally. From this modelling, we estimate that the true contribution to the signal from normal prompt losses is

$$\bar{F} = \langle F_{\text{beam_on}} \rangle - \langle F_{\text{beam_off}} \rangle - 1.2 \times \sigma_{\text{beam_off}}, \quad (2)$$

where $\langle F_{\text{beam_on}} \rangle$ is the average FILD signal when the beam of interest is turned on and $\langle F_{\text{beam_off}} \rangle$ and $\sigma_{\text{beam_off}}$ are the average and standard deviation of the FILD signal when that beam is off.

The radial excursions caused by an individual mode during a single transit provide a novel and quantitative experimental validation of the SPIRAL code for simulating the AE interaction with FIs. The calculated radial excursions using equation (1) for the $n = 2$ RSAE of figure 15 are shown in figure 19. With a mode amplitude ($\delta T_e/T_e$) of 1%, the RSAE

Figure 19. The radial kicks (ζ) inferred from equation (1) for the $n = 2$ RSAE shown in figure 15 (blue diamonds) are plotted versus the ones calculated from SPIRAL simulations (open squares). A representative error of the experimental inferred radial kick and the standard deviation from each SPIRAL Monte Carlo simulation are plotted.

causes a ~ 10 cm radial excursion to the FIs. The $n = 5$ TAE of figure 15 produces the same amount of radial excursion at a mode amplitude of 0.7%. The radial excursions due to the $n = 2$ RSAE are also calculated using the SPIRAL code. In the simulation, the radial kick is defined as the radial distance from the ion birth location on the midplane to the FILD2. In practice, the particles are not all born on the midplane. Therefore, the particles that are born away from the midplane are moved to the midplane along their orbits for the radial kick calculations. The simulated radial kicks are plotted in figure 19, showing overall good agreement to the experiments in not just the general trend, but also the absolute values. The small discrepancies at lower mode amplitudes are probably due to the details in the SOL in front of the beam that lead to possible overestimate of the ionization rate there in the simulation. The AE mode structure evolves on a time scale much longer than that of the mode amplitude; thus, the gradient of fluctuating field scales linearly with the mode amplitude for the time duration on the order of one poloidal transit. Therefore, the radial kick also scales linearly with the field gradient as can be visualized in figure 12—the most pronounced kicks by the modes (deflections of orbit) happen at locations where the gradients of fluctuating fields are steepest.

4. Summary and discussion

A prompt non-resonant loss mechanism induced by Alfvén eigenmodes has been observed in DIII-D. The losses have pitch angle and gyroradius similar to ordinary prompt losses from the same neutral beam, and the losses show a toroidal-angle source dependence and variation with the plasma current similar to ordinary prompt loss. Furthermore, the rise/decay time of the loss is less than $100 \mu\text{s}$, consistent with one poloidal transit time. In contrast to the commonly recognized coherent loss mechanism, whereby counter-going particles interact with the mode over a large number of iterations and transit to trapped orbits that are located in the loss cone, the loss mechanism found here occurs on a single poloidal bounce.

The FILD data identifies an important transport effect for fast ions that can be understood using full-orbit-following SPIRAL simulations. The data show that the fast-ion orbit is quite sensitive to the fluctuating field of the mode. An $n = 2$

RSAE with mode amplitude as low as $\delta B_{\text{peak}}/B \leq 1 \times 10^{-3}$ can cause a radial displacement of ~ 10 cm. Such large kicks applied to a large fraction of the distribution function may have a significant impact on the internal redistribution of energetic particles. Furthermore, the radial displacement measured using this prompt coherent loss provides a good test bed of the modelling of AE mode structures and the fast-ion transport they induce. In this paper, a novel and quantitative experimental validation of the SPIRAL code has been done for the first time for simulating AE and fast-ion interaction during a single poloidal transit. In this work, the mode structure from the ECE measurement agrees well with linear calculations from NOVA. These AE modes are not strongly driven (compared to other MHD activities, e.g. the fishbone mode) and therefore, the perturbative approach as used in NOVA gives solutions close to the real eigenmodes structures. However, it remains interesting to compare these measurements with numerical simulations that include non-linear saturation mechanism.

The AE interactions nearly double the fast-ion losses at the FILD location through a non-resonant loss channel. (For reference, the predicted classical prompt loss from TRANSP is about 7% in these discharges.) It demonstrates that non-resonant particles can form appreciable transport/loss if they encounter a loss boundary, which prevents them from returning to the starting point. Attention should be paid to the additional heat load and potential damage to the in-vessel wall from this mechanism. Conventional coherent losses are less likely to create hot spots because the losses rotate toroidally, so the heat load is spread over a large area. The prompt coherent losses hit the wall, instead, at a fixed location, which depends on the beam geometry and the magnetic field configuration. For the primary discharge 146096 presented in this paper, the estimated loss spot is ~ 0.5 m². The 80 keV beam at 700 kA in DIII-D is like the 1 MeV NBI at 2.5 MA in ITER in terms of banana orbit width to minor radius scaling. Therefore, the same loss process could take place if NBI is injected during the current ramp in ITER. Changes in scale size and mode location in AE activities need also to be considered for extrapolating these results to ITER. Furthermore, the same non-resonant loss mechanism can radially displace the beam ions and alpha particles outward and potentially be lost if they encounter a loss boundary due to edge perturbations such as edge-localized mode (ELM), TBM and RMP. Since the 3.5 MeV alpha particles and 1 MeV beam ions in ITER are potentially damaging, the impact on wall-loading thresholds due to this prompt non-resonant loss mechanism should be investigated for ITER.

These non-resonant losses may affect mode stability. Generally, only resonant ions are considered in AE stability calculations. Although non-resonant ions exchange energy with an AE wave, energy gained during one phase of the wave is lost during the opposite phase for these confined non-resonant ions, so the net energy exchange is negligible. However, in the presence of a loss boundary, non-resonant ions interact with the wave for less than a full cycle, so the net energy exchange is non-zero. Because non-resonant ions occupy a larger portion of fast-ion phase space than resonant ions, this effect may make a significant contribution to the fast-ion drive of Alfvén eigenmodes.

These measurements also have novel and important diagnostic implication. Previously, the radial excursion of fast

ions due to individual modes in a well-defined time cannot be determined conclusively on major magnetic fusion facilities. In this paper, we have shown that such a determination is possible by proper arrangement of a neutral-beam injector and a FILD. Since many facilities are equipped with neutral beams and loss detectors, with proper adjustment of the toroidal displacement of the first orbits, this technique can be applied to measure the fast-ion radial excursion produced by AEs and other instabilities by measuring prompt coherent losses. This new diagnostic technique also has possible application for probing the plasma response to RMPs, since the perturbations caused by RMPs can have similar or even larger amplitudes than the AE amplitudes studied here. The new diagnostic method, which may be referred to as a light-ion beam probe, allows one to measure the profile of various internal oscillating fields in analogy to the heavy-ion beam probe (HIBP) [45], using a simpler experimental setup (and neutral-beam ions which are lighter than the ones used for HIBP).

Based on the fast response of the loss signal to beam switch-on/off (ability to capture to the fast mode growing/damping) and the linear dependence of the loss amplitude on the mode amplitude, one can expect, by varying the neutral-beam power therefore controlling the mode amplitude, it might be possible to resolve the mode growth/damping rate from the associated loss measurements. In fact, there are already some preliminary data suggesting the possibility. This will provide a constraint for modelling the AE mode amplitude in addition to ECE measurements.

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Appendix. Perturbed FILD signal from conservation of phase space

This appendix presents an algorithm for relating orbit-code calculations to the measured flux at the scintillator. It also clarifies the approximations implicit in the expression that relates the modulated flux to the ionization gradient (equation (1)).

Deuterons that ionize at a neutral beam and strike the FILD scintillator escape the plasma on trajectories governed by the Lorentz force law, with negligible probability of colliding with plasma particles. Since the equations of motion are Hamiltonian, phase space is conserved by the mapping that ‘connects’ ions born in the neutral beam to ions that strike the FILD scintillator. In other words, the six-dimensional volume formed by the detector and its collimating apertures is equal to the six-dimensional volume of neutral-beam ionizations that emits the particles measured by the FILD (figure A.1).

The number of ions that strike the scintillator screen in a time dt in a differential phase space volume is $(\cos \theta dA)(v dt)(v^2 d\Omega dv)$, where dA is the differential area of a spot on the scintillator, Ω is the detector solid angle (defined by the collimating apertures), θ is the angle formed

Figure A.1. Schematic diagram of the differential volume in neutral-beam phase-space that emits ions into the differential phase-space volume measured by the detector. In the presence of Alfvén eigenmodes, the lost ions originate from a different volume in phase-space.

by the ion orbit and the scintillator normal, and v is the ion's speed. These ions originate from a phase-space volume $dA_b(v_b dt)(v_b^2 d\Omega_b dv_b)$, where dA_b is a small area in the neutral-beam footprint that emits ions into a solid angle $d\Omega_b$ and v_b is the speed of the orbit at the beam. By conservation of phase space, these volumes are equal. Therefore, the differential number that strike the scintillator dN is $dN = dA_b(v_b dt)(v_b^2 d\Omega_b dv_b)$. The scintillator flux is the sum of all the beam volumes 'viewed' by the measured orbits. Different volume elements in the beam footprint produce ions at different rates, so they are weighted by the ionization rate $I(\vec{r}, \vec{v}_b)$. Hence, the scintillator flux F is

$$F = \int I dA_b dl v_b^2 d\Omega_b dv_b, \quad (\text{A.1})$$

where the integration is over all phase-space dimensions and $dl = v_b dt$ is the differential length of the orbit as it crosses the beam.

In principle, one can solve equation (A.1) by following ions from their birth points but, because the scintillator occupies a small volume in phase space, this approach is terribly inefficient. Since the system is conservative, the orbits are reversible. It is far more efficient to trace orbits backward from the scintillator until they intersect with the beam source. For calculation of prompt losses, this has been standard procedure in the FILD community for decades [46]. For prompt losses from a beam, one traces the orbit backwards in time until it reaches the spatial location of the neutral-beam source. The beam source has a finite 'footprint' in space (a profile in both height and width) and also a finite volume in velocity space (due to beam divergence) that is distributed around a central velocity vector. To a good approximation, the spatial and velocity-space dependencies of the ionization source are separable, $I(\vec{r}, \vec{v}) = I_r(\vec{r})I_v(\vec{v})$. Since the energy spread of full-energy neutrals and the angular divergence ($\leq 1^\circ$) are both small, the beam velocity-space function I_v is essentially a delta function. Accordingly, one usually checks at each time step whether the ion velocity vector $\vec{v}$ matches

the velocity vector $\vec{v}_b$ of injected neutrals, then records a 'hit' if it does. Each hit is weighted by the spatial profile I_r of the ionization source. If the FILD spot is narrowly collimated and spatially localized ($\Delta\Omega$ and ΔA both small), then equation (A.1) simplifies to

$$F_0 = \Delta A \Delta\Omega \int I_r dl, \quad (\text{A.2})$$

where the integral is over the spatial volume where the orbit matches the velocity of the injected beam.

In the present case, interaction with AEs modifies the orbit so that it intersects a different portion of neutral-beam phase space. In numerical work, this does not alter the basic algorithm: one still follows the perturbed orbit through the beam footprint, recording locations where the orbital velocity matches $\vec{v}_b$. To develop analytical understanding of the fluctuating signal, consider the perturbed orbit trajectory in phase space $\vec{\Gamma}$. It consists of the unperturbed orbital trajectory $\vec{\Gamma}_0$ and a perturbed phase-space distance $\vec{\zeta}(\vec{r}, \vec{v})$, $\vec{\Gamma} = \vec{\Gamma}_0 + \vec{\zeta}$. Assume the orbit perturbation is small and expand I_r in a Taylor series. Then the perturbed flux is approximately

$$\Delta F = F - F_0 \sim \int \vec{\zeta} \cdot \nabla I_r dA_b dl v_b^2 d\Omega_b dv_b, \quad (\text{A.3})$$

where the integral is over the unperturbed orbit and the derivative ∇ is over all phase-space variables. Taking the velocity-space integral as a narrow filter that selects positions where the orbital velocity matches $\vec{v}_b$ (as before), equation (A.3) becomes

$$\Delta F/F_0 \sim \int \left(\zeta_R \frac{\partial I_r}{\partial R} + \zeta_\phi \frac{\partial I_r}{\partial \phi} + \zeta_z \frac{\partial I_r}{\partial z} \right) dl / \int I_r dl. \quad (\text{A.4})$$

In general, the AEs move the orbits that match $\vec{v}_b$ a radial distance ζ_R , a toroidal distance ζ_ϕ , and a vertical distance ζ_z . However, for maximum sensitivity to perturbations, the equilibrium orbit is selected to pass through the centre of the neutral-beam footprint. At this location, the toroidal and vertical ionization gradients $\partial I/\partial \phi$ and $\partial I/\partial z$ are zero. For this special case, equation (A.4) reduces to

$$\Delta F/F_0 \sim \int \left(\zeta_R \frac{\partial I_r}{\partial R} \right) dl / \int I_r dl \sim \zeta_R \frac{\partial I_r / \partial R}{I_r}, \quad (\text{A.5})$$

which is equation (1) where $\vec{F} = F_0$ (different notation). For other choices of equilibrium orbit, other terms equation (A.4) can be important.

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