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NBI-driven Ion Cyclotron Instabilities at W7-AS

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The micro-instabilities driven by nonequilibrium ion distributions play an important role in fusion plasmas. Such distribution originating due to intense NB or ICR heating or due to alpha-particle slowing-down under reactor conditions can influence plasma confinement and the evolutions of these distributions. Besides, the investigation of the micro-instabilities may serve as a diagnostic tool for understanding the dynamics of the fast ion component. The lower hybrid (LH) turbulence driven by a rather weak diagnostic hydrogen beam detected at W7-AS stellarator by the Collective Thomson Scattering (CTS) technique [1] became the starting point for further more detailed both experimental and theoretical investigations.

1. Experimental conditions. Experiments were performed in a hydrogen plasma ($n_e \leq 5 \cdot 10^{13} cm^{-3}$) supported by a number of heating systems or their combination such as tangential NBI (hydrogen beam, ≈ 55 *keV*, up to 0.5 *MW*, launch angle $\approx 30°$ with respect to magnetic field), new transverse NBI (hydrogen beam, ≈ 55 *keV*, up to 0.6 *MW*, launch angle $\approx 80°$), and ECRH (140 *GHz*, up to 0.5 *MW*). ECR heating was slightly off-axis in order to improve the CTS conditions in which the same gyrotron was used as a source of the probing radiation. The CX diagnostic neutral hydrogen beam was also used as a driver of enhanced LH-turbulence. In addition to the CTS system which registered small scale (≈ 1 *mm* corresponding to strictly fixed $k_\perp$) electron density fluctuations inside the plasma volume, the broad-band loop antenna placed outside the plasma was used for the registration of ion cyclotron emission (ICE).

2. The main experimental results. The detailed studies of LH turbulence excitation and of enhanced ICE level conditions were performed depending on the W7-AS magnetic configuration, plasma parameters and NBI launching scenarios (tangential NBI, nearly radial NBI, diagnostic perpendicular beam, and combined). An example of the CTS signal in the frequency channel corresponding to the lower hybrid frequency is presented in Fig.1. Here the developed LH turbulence is found to be stationary within the diagnostic NB injection (240-290 *ms*, 340-390 *ms*), while the injection of the radial heating NB (450-650 *ms*) results in the enhanced LH turbulence level only in the very beginning during the beam slowing down time which is well resolved by the detection system. In other experimental conditions radial NBI can provide a continuously enhanced CTS signal. All CTS spectra from LH turbulence are very narrow-band ($\Delta f/f_{LH} \leq 2\%$) what demonstrates its "double-resonance" origin (see [1]).

Two other examples are presented from the ICE system. A typical result of the longitudinal and transverse NBI launching in the lower harmonic numbers is shown in Fig.2. With the parallel NBI (300-700 *ms*) the ICE at lower harmonics (up to 6-8) is registered, with addition of transverse NBI (400-600 *ms*) the number of registered lower harmonics is increased and their intensity becomes higher. IC activity registered in ion cyclotron harmonics adjacent to LH frequency from below with radial NBI is shown in Fig.3. Usually there is a gap between the ranges of lower harmonics and those adjacent to LH with negligible IC activity. It should be stressed that IC activity related to the launch of diagnostic neutral beam was never registered unlike to earlier experiments [1].

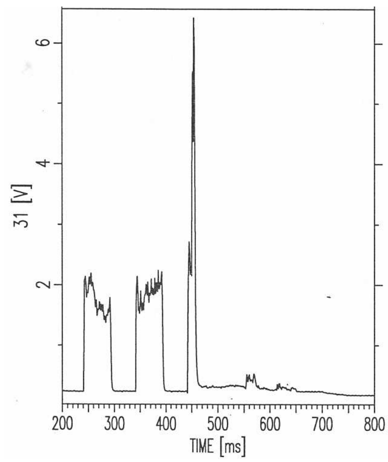

Fig.1 The evolution of CTS signal in the frequency channel corresponding to LH frequency

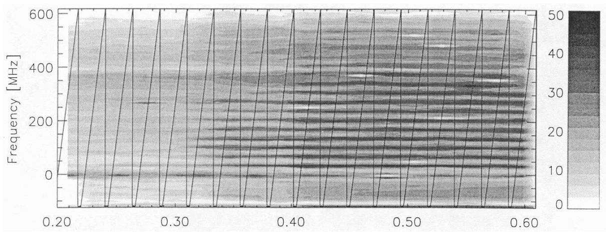

Fig.2 Harmonic structure in the low frequency ICE range

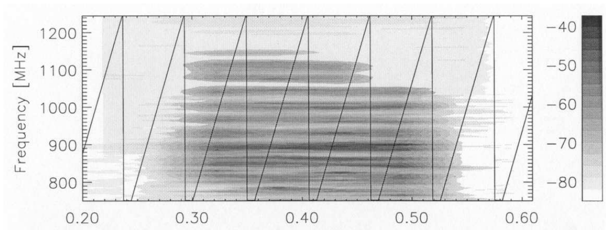

Fig.3 Harmonic structure in the high frequency ICE range

The scan over the magnetic configuration revealed that LH turbulence triggered by diagnostic the NBI and by the transverse heating NBI demonstrated an opposite behavior. The diagnostic NB excites LH turbulence when there is a local minimum of B in the launching plane and ceased to trigger it when this local minimum is decreased or becomes a local maximum. In the latter case convective losses of ripple trapped fast ions are significantly lower. The radial heating NB being far enough from trapping, nevertheless, also reacts to the local magnetic configuration: it generates LH turbulence in the initial stage (during a slowing-down time) in the presence of a local minimum of B in the launching plane and supported stationary LH activity in configurations with local maximum of B.

The LH turbulence triggered by both radial and diagnostic NBs is strongly suppressed with the injection of the longitudinal NB.

3. Stability analysis for ion distributions originating from different NB injectors. The NBI-driven fast ion distributions have been numerically calculated both at the transient and stationary stages using a time-dependent bounce-averaged Fokker-Planck code [2] for modeling the collisional slowing-down of the beam ions taking into account trapped ion losses. Unlike the diagnostic NB, for which the collisional slowing-down is negligible compared to convective losses of ripple trapped fast ions, the fast ion distribution functions of the other NBI's are governed mainly by collisions except of the switching-on phase (typically few *ms*). Unstable roots in the vicinity of ion cyclotron harmonics following from the solution of the dispersion relation are investigated with fast ion distribution functions calculated for different NBI scenarios.

The most unstable modes are found under the double-resonance condition when the LH frequency equals to a high ion cyclotron harmonic frequency. In this case, an absolute instability of hydrodynamic type arises with a maximum growth rate roughly proportional to square-root of the beam density provided that the instability condition is satisfied:

$$\int J_n^2(k_\perp v_\perp/\omega_{ci})\,\partial f/\partial v_\perp^2\, d^3\mathbf{v} > 0.$$

Simulations show that unstable distributions may be generated by the radial NBI (strongly pronounced in the switching-on phase, while the instability condition for a steady state is very sensitive to the injected beam energy composition and to the trapped fast ion loss rate). Ion distributions resulting from the longitudinal NBI never provide the hydrodynamic instability, moreover, they reduce the growth rates or even stabilize the LH activity driven by the radial and the diagnostic beams. If the fast ions of the diagnostic beam are trapped in the local minimum of B collisional relaxation is negligible; it triggers steady-state LH turbulence if the beam density is above the threshold value which is much lower than corresponding values for the nearly radial NBI.

The origin of the harmonic structure in the observed ICE spectra may be attributed to kinetic instabilities of ion Bernstein waves, which are driven at ion cyclotron harmonics by the fast ion distributions resulting from both radial and longitudinal NBI. The growth rates of such instabilities proportional to the beam density are calculated within a perturbation approach in which fast ion distribution contributes only to anti-Hermitian part of the dielectric tensor.

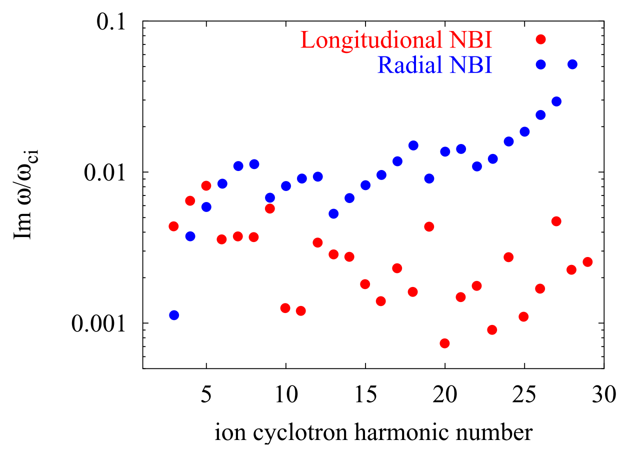

Fig.4. Dependence of maximum increment of kinetic instability on harmonic number

An example in Fig.4 presents maximum increments with respect to propagation angles and wave numbers depending on ion cyclotron harmonics up to the LH for the steady-state ion distributions obtained for the longitudinal (red) and the radial (blue points) NBI's. In both cases, the instability is driven by positive gradients of the distribution function with respect to $v_\perp$.

4. Conclusions. The numerical modeling of ion distributions resulting from different NBI scenarios at W7-AS shows that these distributions can trigger a strong instability of the hydrodynamic type close to LH with a growth-rate being proportional to the square-root of the beam density. Such a situation is realized with the injection of the strictly transverse diagnostic beam and of a quasi-transverse heating beam and corresponds to the experimental observations. The threshold densities are strongly different for the diagnostic beam, which with poor confinement possesses a strongly peaked distribution, and for the radial heating beam with the distribution function resulting from the slowing-down process. It should be noted, however, that the theoretical modeling of the fast ion distribution function resulting from the radial NBI in the magnetic configuration with maximum of B in the injection plane does not provide the "double-resonance" instability, while it is clearly pronounced in the experimental measurements.

The convective type instabilities in the vicinity of lower ion-cyclotron harmonics are found even for steady-state distributions resulting from both longitudinal and radial NBI's. These instabilities are realized due to the corresponding contribution of the beam-driven ion distributions to the anti-Hermitian part of dielectric tensor. It should be noted, however, that this analysis demonstrates only the principal possibility to have enhanced activity at ion-cyclotron harmonics inside the plasma volume. In order to apply this to experimental results from the ICE system the analysis of wave propagation in a nonuniform plasma towards the plasma edge is needed which is beyond of the scope of the presentation.

The last observation should be made concerning the registration of LH turbulence triggered by diagnostic NB. The analysis of the beam-driven ion distribution function shows that the hydrodynamic instability is realized only when the fast ions are trapped in the local minimum of B. This means that the unstable ion distribution is localized in the launching plane while the LH turbulence is measured in the toroidally separated CTS section. Therefore, the excited small-scale LH waves can propagate around the torus, or they possesses some global structure. An additional evidence supporting this is the absence of a LH signal in the ICE system with a new position of the loop antenna.

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References

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