

Runaway electron-driven plasma instabilities at TCV: an exploratory hot plasma analysis

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Introduction. Over the past few years, the investigation of runaway electron (RE) physics [1] at the Tokamak à Configuration Variable (TCV, Lausanne) has been complemented with direct measurements of plasma waves associated with RE-driven kinetic instabilities [2-4], using an in-vessel single-loop antenna. This work reports developments achieved within the framework of this activity over the last year. First, measurements obtained with the current antenna, in combination with a 12-bit acquisition system, are presented, beyond those already reported in [5]. Second, a phenomenological interpretation model of observed waves is proposed, in terms of overlapping Ion Bernstein Waves (IBW). Finally, the concept resulting from a redesign activity of the current single-loop antenna and selected for its implementation is presented.

Interpretation as Ion Bernstein Waves. Instabilities at TCV above the ion cyclotron frequency $f_{ci} = ZeB/(2\pi m_i)$ typically emerge into multiple spectral clusters extending over several tens, or hundreds, of MHz. In almost all observations, the frequency spacing between coherent waves is comparable to the deuterium f_{ci} (Fig. 1), which in the investigated scenarios is typically 9-15 MHz, depending on radial position. This motivated the search for a connection between the IBW

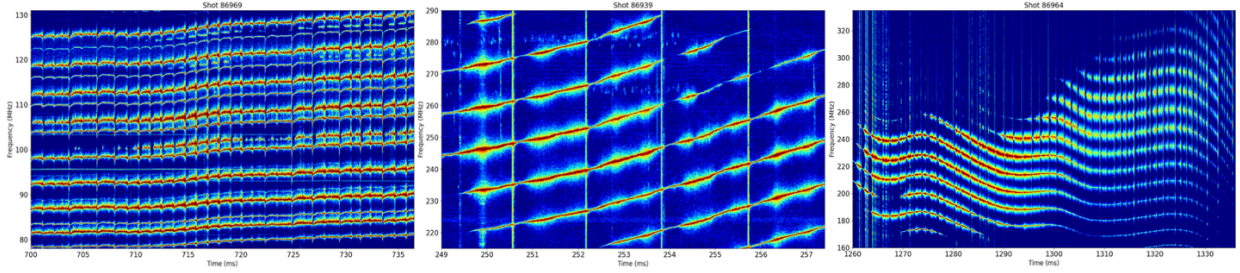


Fig. 1. Three examples of coherent RE-driven instabilities measured using the current single-loop antenna.

and the observed emissions, following recent theoretical stability studies based on a hot plasma description [6], in which destabilization is expected at multiple coalescence frequencies between the dispersion branches of hot Electron Plasma Waves and IBW. The instabilities should be driven at any ion cyclotron harmonic $f_n = n f_{ci}$ through Cherenkov resonance, with RE energy distributions peaked at a few MeV. Rather than assuming a single IBW population locally excited at a specific radial location, a proposed interpretation considers the possibility of several IBW clusters driven at different radial positions, as a result of the varying location of the RE beam during the shot. In this picture, each cluster is associated with distinct plasma conditions and k_{\perp} , and the observed spectra arise from superposition of multiple overlapping harmonic families. To investigate this hypothesis, a simplified model based on the harmonic structure of IBW has been developed. For different plasma regions, f_{ci} and the ion Larmor radius $\rho_i = v_{thi}/\omega_{ci} = \sqrt{2T_i/(m_i\omega_{ci}^2)}$ are calculated. The spectral contribution of the n^{th} harmonic f_n to the modeled IBW spectral power density is weighted by $J_n^2(k_{\perp}\rho_i)$, where $J_n(x)$ is the n -order Bessel function of the 1st kind, and is here represented by a Lorentzian profile $L_n(f) = \gamma/[(f - n f_{ci})^2 + \gamma^2]$ with half-width $\gamma = \gamma_0[1 + 0.5(n_i - n_{ref})/n_{ref}]$, where n_i is the ion density, $\gamma_0 \propto f_{ci}$ defines a spectral linewidth proportional to f_{ci} through an empirical scaling parameter (in order to assume a constant fractional linewidth across the harmonic spectrum), γ includes a secondary additional density-dependent broadening effect, while n_{ref} is defined as an average density value of the region contributing to the observed emissions. n_{ref} is used for normalizing the density-related broadening and its value is taken as the ion density n_i close to mid-radius, to account for an effective average over the relevant wave-particle interaction volume. The resulting spectrum is $S(f) = \sum_{\alpha} \sum_n J_n^2(k_{\perp,\alpha}\rho_{i,\alpha}) L_{n,\alpha}(f)$, where the sums extend over n harmonics and α clusters. Although simple and not including the full IBW dispersion relation, the model nevertheless retains the main qualitative features of ion cyclotron harmonics modulated by finite Larmor radius effects. As an example, the model is applied to discharge #86969 at $t = 700$ ms. The frequencies of coherent emissions are extracted from the measured PSD and compared with the simulated

spectrum. Fig. 2(a) shows the result obtained by superimposing four independent IBW clusters. Different colors indicate the contributions of individual clusters and the grey bands are the observed wave frequencies at $t = 700$ ms. The combined signals of the IBW clusters with such selected parameters are sufficient to reproduce the experimental spectrum very accurately. At this exploratory stage, both the radial position and k_{\perp} are treated as free (albeit physically realistic) parameters, with the primary goal of reproducing the experimental spectra and assessing whether IBW-like waves provide a viable interpretation of the instabilities. Future work will adopt a more

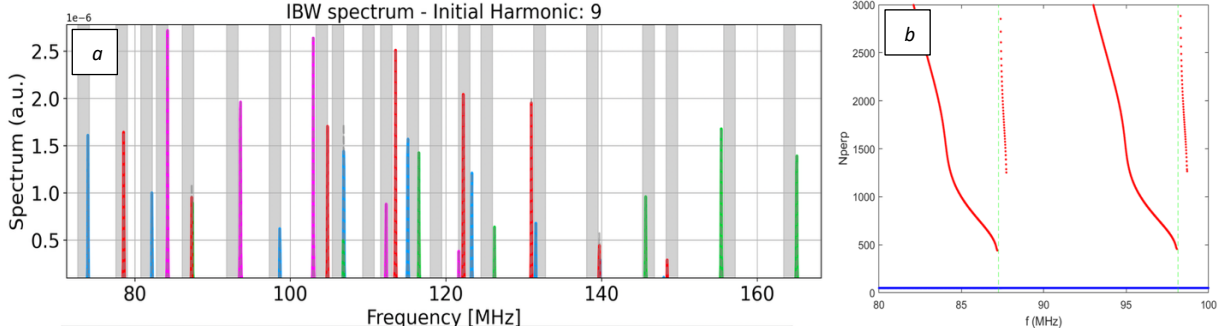


Fig. 2. (a) synthetic spectrum obtained by superimposing harmonics of four independent IBW clusters with the following parameters: $B=1.08$ T, $k_{\perp}=4883$ m^{-1} , $n_i=3.6$ $E18$ m^{-3} , $T_i=0.28$ keV (blue); $B=1.27$ T, $k_{\perp}=5475$ m^{-1} , $n_i=5.2$ $E18$ m^{-3} , $T_i=0.45$ keV (green); $B=1.23$ T, $k_{\perp}=3392$ m^{-1} , $n_i=4.4$ $E18$ m^{-3} , $T_i=0.45$ keV (magenta); $B=1.14$ T, $k_{\perp}=4164$ m^{-1} , $n_i=3.7$ $E18$ m^{-3} , $T_i=0.43$ keV (red). The grey bands indicate the emission frequencies observed during shot #86969 at $t=700$ ms. (b) IBW dispersion branches at 87 MHz and 98 MHz, both identified as unstable by REDHPW simulations using plasma parameters from discharge #86969 at $t = 700$ ms.

physics-based approach by simulating the radial profile of the drive to identify the regions most likely to excite specific clusters. IBW are plasma eigenmodes with no counterpart in vacuum. As for other RE-driven waves, the possibility of detecting IBW outside the plasma through our RF antenna relies on a coupling mechanism between plasma waves and EM waves. While this process is experimentally well established, the underlying physics is still an active area of investigation in the community. Although further investigation is required, the synthetic spectra suggest that an IBW-based interpretation provides a plausible framework for interpretations. Unstable IBW in this range are also predicted using the code REDHPW [6], able to solve the full hot dispersion relation. Considering again shot #86969 at $t = 700$ ms, IBW instabilities are found, with a growth rate near $(2-3) \times 10^5 s^{-1}$, at 87 MHz and 98 MHz (Fig. 2(b)). These frequencies are located close to the observed deuterium cyclotron harmonics $(8-9) f_{ci}$. The low group velocity $v_{\perp} \approx 10^{-6} c$ of these waves allows interaction with RE for a time long enough to produce both quasilinear effects, such as modifications of RE distribution function and wave amplitude saturation, and nonlinear effects. N_{\parallel} is assumed to be 1.0013, resulting in Cherenkov resonance with RE at ≈ 10 MeV.

Star-Loop Antenna. An upgrade of the existing single-loop antenna is underway to improve the coupling to EM signatures in the sub-GHz range. The antenna redesign has now been completed

and the refurbishment will be fulfilled through the installation of a new configuration. In [5], several geometries were investigated through *CST* simulations, leading to the identification of candidate designs.

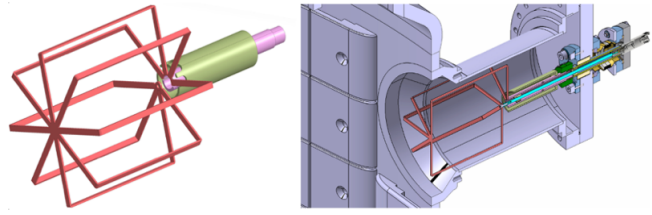


Fig. 3. Sketch of the *Star-Loop*, showing the front view (left) and a cross-section of the system in the TCV port (right).

However, the final configuration, referred to as *Star-Loop*, was not included among those, as it was investigated following additional simulations. The *Star-Loop* consists of four loops mounted with a relative angular offset of 45° (Fig. 3). The original motivation for exploring this geometry was to enable coupling of different polarizations with a single setup. Later it also demonstrated superior performance compared with previously geometries [5]. All elements are electrically interconnected and combined into one output and a single coaxial line. Although this setup precludes independent measurements of different polarizations, it maximizes the signal-to-noise ratio in the band, which is the primary requirement. The manufacturing is underway and the installation in the vessel is scheduled before the end of 2026.

Conclusions. New measurements of RE-driven instabilities have been obtained at TCV using the current single-loop antenna. A phenomenological interpretation of the observed emissions is proposed in terms of multiple overlapping IBW clusters driven at different locations in the plasma. This simple framework is able to reproduce a substantial fraction of frequency structures and also simulations performed with the *REDHPW* code confirm IBW as a viable interpretation. A redesign of the current antenna has been completed, leading to the new *Star-Loop* geometry, which is currently under construction and is expected to be installed before the end of 2026.

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References

- [1] J. Decker et al., *Nucl. Fusion* **64** 106027 (2024)
- [2] P. Buratti et al., *Plasma Phys. Control. Fusion* **63** 095007 (2021)
- [3] W. Bin et al., *Phys. Rev. Lett.* **129** 045002 (2022)
- [4] W. Bin et al., *Rev. Sci. Instrum.* **93** 093516 (2022)
- [5] W. Bin et al., *Proc. 51st EPS Conference on Plasma Physics* P4.201 (2025)
- [6] C. Castaldo et al., *Nucl. Fusion* **64** 086003 (2024)