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

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[11]See the author list in: C. Theiler et al., Nucl. Fusion 66 116007 (2026) [12]See authors in: See author list in: N. Vianello et al. Nucl. Fusion 66 116010 (2026)

Over the past few years, the investigation of runaway electron (RE) physics [1] at TCV (Lausanne) has been complemented with measurements of plasma waves associated with RE-driven kinetic instabilities [2-4], using an in-vessel single-loop antenna. Developments have been achieved over the last year. First, measurements obtained with the current antenna 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), and a stability simulation of RE-driven IBW performed using the *REDHPW* code [6] with the TCV plasma scenario is reported (Fig. 1). Finally, the concept resulting from a redesign activity of the current single-loop antenna and selected for its implementation is presented.

HOT PLASMA WAVE INTERPRETATION

Instabilities at TCV above the ion cyclotron frequency typically emerge in multiple clusters (Fig. 2), with a frequency spacing comparable to that frequency (9-15 MHz) → this motivated the search for a connection between emissions and Ion Bernstein Waves (IBW), which are foreseen unstable [6] at coalescence frequencies between hot Electron Plasma Waves and IBW, at any ion cyclotron harmonic nf_{ci}.

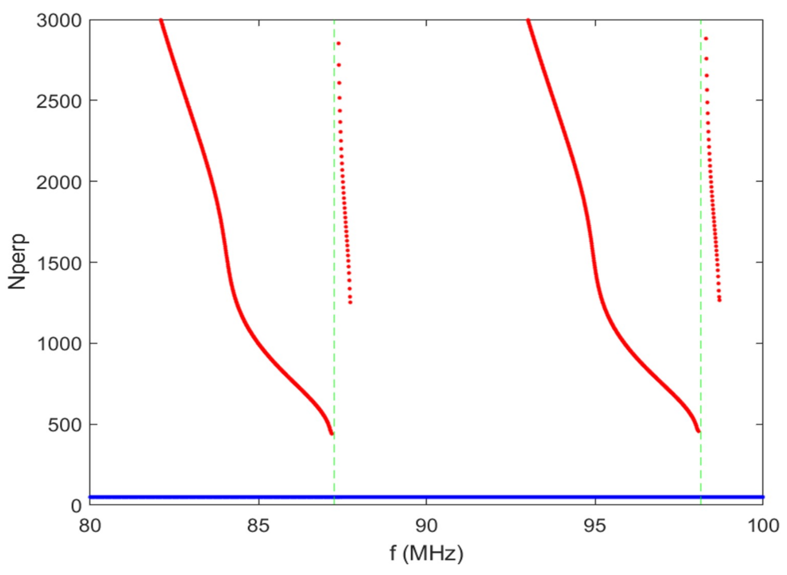

Fig. 1. IBW branches at 87 MHz and 98 MHz identified as unstable running the REDHPW code [6] with plasma parameters from TCV discharge #86969 at t = 700 ms.

A simple interpretation model is proposed: observed spectra would result from contributions of several IBW clusters, each one driven with distinct $k_\perp$ at different radial positions.

$$f_{ci} = \frac{ZeB}{2\pi m_i} \text{ and } \rho_i = \frac{v_{thi}}{2\pi f_{ci}} = \sqrt{\frac{2T_i}{m_i 4\pi^2 f_{ci}^2}}$$ are radially calculated.

The spectral contribution of the n^{th} harmonic $f_n = nf_{ci}$ to the PSD is represented by a Lorentzian profile $L_n(f)$ and weighted by $J_n^2(k_\perp \rho_i)$, where $J_n(x)$ is the n-order Bessel function of the 1st kind.

$$L_n(f) = \frac{\gamma}{(f - nf_{ci})^2 + \gamma^2}, \text{ with half-width: } \gamma = \gamma_0\left(1 + 0.5\frac{n_i - n_{ref}}{n_{ref}}\right)$$

where n_i is the ion density; $\gamma_0 \propto f_{ci}$ is a spectral linewidth proportional to f_{ci} through an empirical parameter; γ includes a secondary density-dependent broadening effect; n_{ref} is taken as n_i close to mid-radius and is used to normalize broadening.

The resulting spectrum is:

$$S(f) = \sum_\alpha \sum_n \frac{J_n^2(k_{\perp,\alpha}\rho_{i,\alpha})\gamma_\alpha}{(f - nf_{ci,\alpha})^2 + \gamma_\alpha^2}$$

To show an example, the PSD measured at t = 700 ms is shot #86969 is considered and reproduced using the model (see Fig. 3)

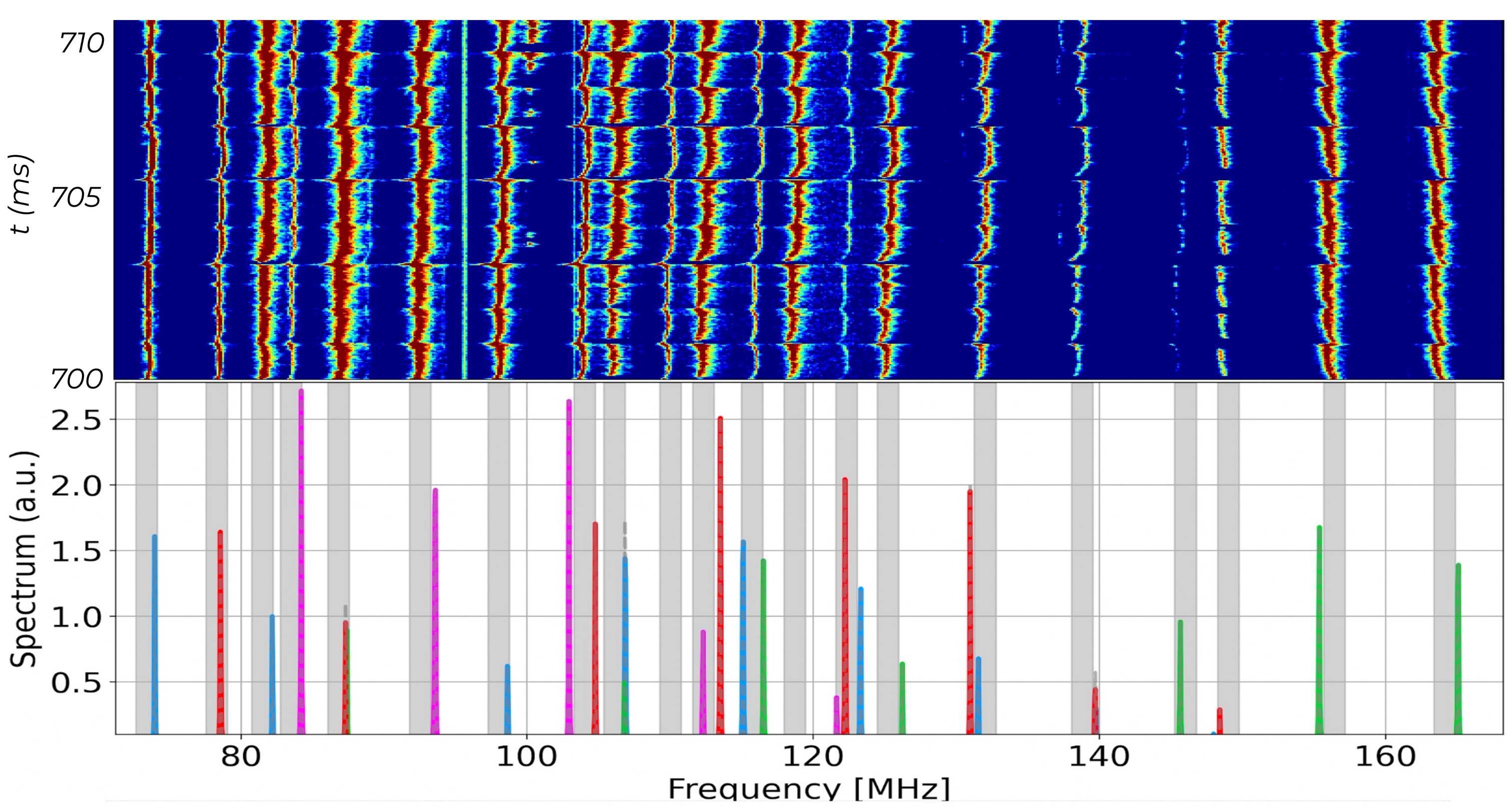

Fig. 3. Spectrogram of shot #86969 (top) and synthetic spectrum (bottom) obtained as sum of four independent IBW clusters evaluated using the following parameters: B = 1.08 T, $k_\perp$ = 4883 m^{-1}, n_i = 3.6 x 10^{18} m^{-3}, T_i = 0.28 keV (blue); B = 1.27 T, $k_\perp$ = 5475 m^{-1}, n_i = 5.2 x 10^{18} m^{-3}, T_i = 0.45 keV (green); B = 1.23 T, $k_\perp$ = 3392 m^{-1}, n_i = 4.4 x 10^{18} m^{-3}, T_i = 0.45 keV (magenta); B = 1.14 T, $k_\perp$ = 4164 m^{-1}, n_i = 3.7 x 10^{18} m^{-3}, T_i = 0.43 keV (red). The grey bands indicate the frequencies observed at t=700 ms.

NEW ANTENNA CONFIGURATION

An upgrade of the existing single-loop antenna is ongoing, to improve the coupling to EM signatures of kinetic instabilities in the sub-GHz range. Refurbishment will consist of the installation of a new configuration, referred to as *Star-Loop* (Fig. 4), to be installed in 2026.

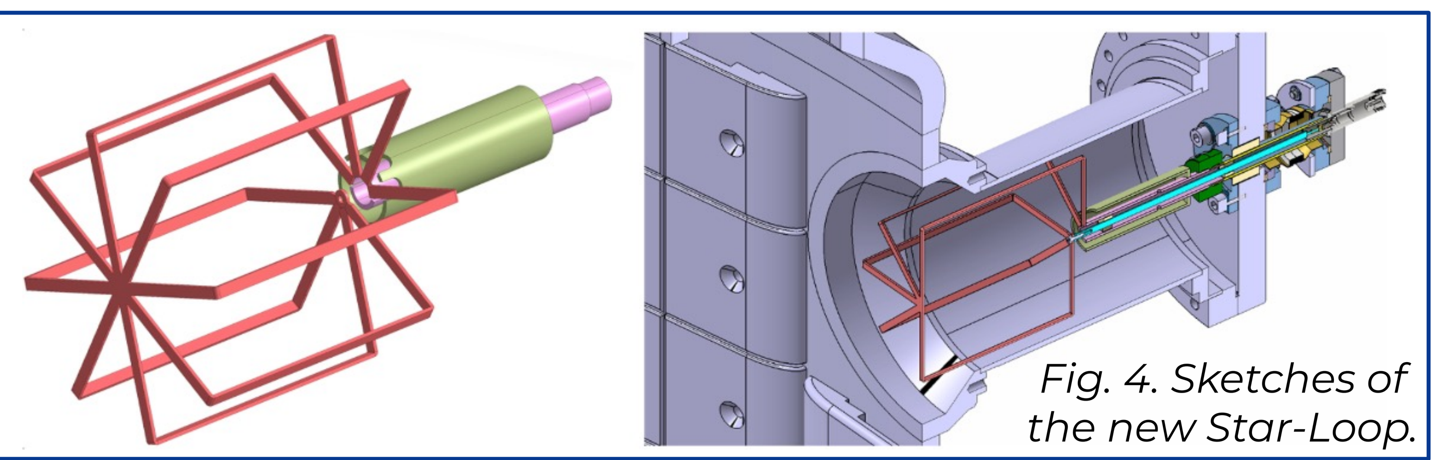

Fig. 4. Sketches of the new Star-Loop.

CONCLUSIONS New measurements of RE-driven instabilities have been obtained at TCV. A phenomenological modeling of the observed emissions is proposed in terms of multiple overlapping IBW clusters driven at different locations. The model reproduces a substantial fraction of frequency structures. Simulations with the *REDHPW* code also confirm IBW as a viable interpretation. A redesign of the current antenna has been completed and the new *Star-Loop* geometry, foreseen to be installed before the end of 2026, is currently under construction.

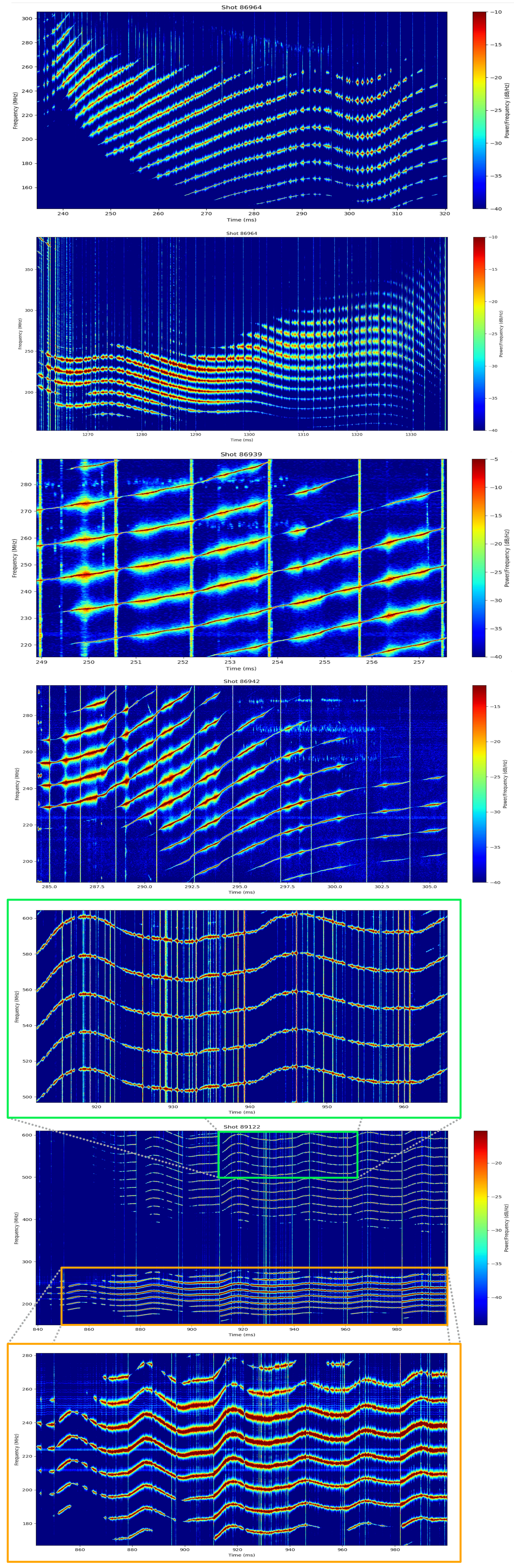

Fig. 2. Coherent RE-driven waves recently measured during different phases of TCV discharges, using the current single-loop antenna.

[1] J. Decker et al., Nucl. Fusion **64** (2024)
[2] P. Buratti et al., PPCF **63** (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., 51st EPS Conference (2025)
[6] C. Castaldo et al., Nucl. Fusion **64** (2024)

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