Enhancement of the TCV Radio Frequency Antenna for Detection of Plasma Instabilities by Runaway Electrons and Electron Cyclotron Waves

W. Bin[1], F. Napoli[2], R. Ragona[3], J. Decker[4], U. Sheikh[4], C. Castaldo[2], A. Cardinali[5], P. Buratti[6], S. Coda[4], M. Gospodarczyk[4], M. Guerini Rocco[7,1], M. Hoppe[8], C. Paraskevopoulos[4], C. Schlatter[4], M. Silva[4], L. Simons[4], A. Jansen van Vuuren[4], C. Yildiz[4], TCV Team[9] and WPTE Team[10]

[1]*CNR, Istituto per la Scienza e Tecnologia dei Plasmi, Milano, Italy*

[2]*ENEA, Fusion and Nuclear Safety Department, Frascati (Rome), Italy*

[3]*Department of Physics, Technical University of Denmark, Lyngby, Denmark*

[4]*Swiss Plasma Center (SPC) - EPFL, Lausanne, Switzerland*

[5]*CNR, Istituto Sistemi Complessi, Politecnico di Torino, Torino, Italy*

[6]*IAPS - INAF Istituto di Astrofisica e Planetologia Spaziali, Roma, Italy*

[7]*Department of Physics, University of Milano-Bicocca, Milan, 20126, Italy*

[8]*Department of Electrical Engineering, KTH Royal Institute of Technology, Stockholm, Sweden*

[9]*See the author list in: B. P. Duval et al., Nucl. Fusion 64 (2024)*

[10]*See the author list in: E. Joffrin et al., Nucl. Fusion 64 (2024)*

Introduction. Between 2024 and 2025, a comprehensive upgrade of an in-vessel RF antenna is being carried out at the Tokamak à Configuration Variable (TCV), operating in Lausanne (Switzerland). The project, undertaken within the framework of EUROfusion, is aimed at improving the diagnostic capabilities in relation to e.m. emissions originating from the plasma. More specifically, the upgraded system is intended to enhance detection of radiofrequency (RF) signatures associated with kinetic instabilities induced by runaway electrons (RE) [1, 3], as well as daughter waves stemming from low-power threshold Parametric Decay Instabilities (PDI) during Electron Cyclotron Heating (ECH) [4]. The presence of kinetic instabilities driven by runaway electrons is of key concern for next-generation fusion reactors, since unstable plasma waves can influence both evolution and redistribution of RE populations. On the other side, the ECH-pumped PDI have been increasingly reported during tokamak operations, including TCV [5], despite being previously underestimated by classical models. At TCV, the original in-vessel antenna underwent an initial refurbishment in 2022, leading to the detection of RE-driven instabilities for the first time at TCV, showing promising performances right from the beginning. The ongoing enhancement aims to further improve the sensitivity of the diagnostic apparatus by extending its capability to acquire signals over longer data acquisitions during plasma discharges and by modifying the front-end configuration of the antenna.

Improvement of the DAS. The first key point of the enhancement project consists of the upgrade of the data acquisition system (DAS). Until 2024, data were acquired using an 8-bit PXIe digitizer. Despite it was offering good temporal and frequency resolution, the measurements were significantly constrained by a limited (non-expandable) onboard memory

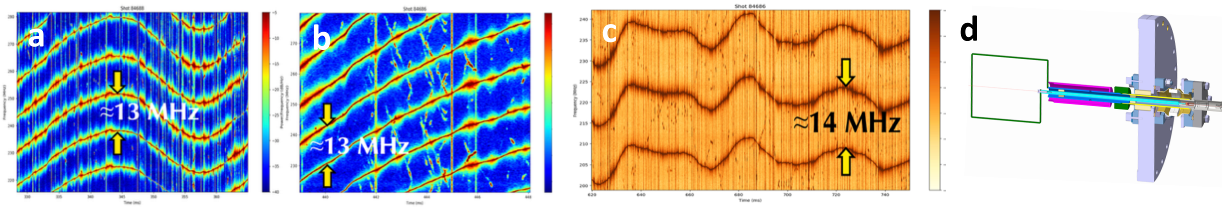

Fig. 1: wave clusters observed in the frequency range ≈ 200-400 MHz (a, b and c). The frequency spacing between unstable waves is ≈ 13 MHz (a and b) and ≈ 14 MHz (c), comparable with the central (≈ 11 MHz) and the high-field side ion cyclotron frequency. Sketch d shows a side view of the current in-vessel antenna

capability. At the end of 2024, this system was replaced with a new Teledyne digitizer board, featuring two channels that share a maximum sampling rate of 10 GSa/s at 12-bit resolution, and 8 GB of onboard memory. The latter enables significantly longer data acquisition, even allowing automatic continuous recording over the full 2 s duration of a TCV plasma discharge, when the Nyquist frequency is limited to a maximum of 1.0 GHz, which in most cases remains sufficiently high to capture a wide range of RE-driven instability families. A number of experimental sessions have already been conducted, during which several families of RE-driven

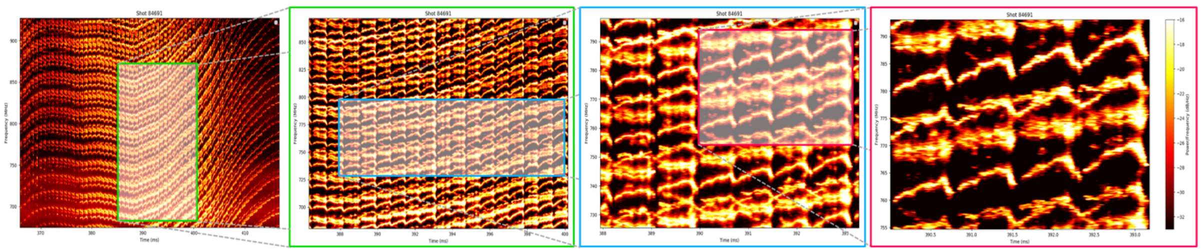

Fig. 2: zoom-ins on increasingly detailed areas of a spectrogram measured during TCV shot 84691. The RE-driven waves extend from ≈ 600 MHz to ≈ 1 GHz. Fine details related to RE dynamics can be measured.

instabilities have been measured in the TCV plasma, using the new DAS. Although the used antenna system was the same as before, yet the diagnostic sensitivity improved compared to the already good sensitivity of the previous system, thanks to the increased dynamic range of the new 12-bit system relative to the former 8-bit one. A few examples of high-quality measurements recently performed are shown in Figure 1 and in Figure 2. When the unstable wave clusters are observed in the range between ≈ 200 MHz and ≈ 400 MHz, the typical frequency spacing between the quasi-monochromatic waves is found to be ≈ 13 MHz, as in Figure 1-a and b, or ≈ 14 MHz, as in Figure 1-d. In both cases, such a frequency spacing is comparable with the ion cyclotron frequency (f_{ci}) at the high field side of the plasma, being

$f_{ci} \approx 11$ MHz at the plasma center for these shots. This observation is consistent with new theoretical predictions [6] for interpreting wave stability in the presence of RE. In this model, the Maxwellian background plasma is described using a kinetic approach rather than the commonly adopted cold plasma fluid model, and both Ion Bernstein Waves and the slow electrostatic Electron Plasma Waves [7] are included among the potentially unstable branches.

New antenna design. The key aspect of the antenna redesign includes replacing the current single-loop with a new setup that should enable detection of waves with higher efficiency and wider bandwidth. Studies are ongoing, focused on investigating several designs, which should improve upon the capabilities of the present loop. The major challenge in measuring hundreds MHz waves with a single antenna is the size of the TCV port, which is too narrow to accommodate a detection system electrically large enough to allow for efficient direct coupling at these frequencies. As a consequence, any setup that fits within the port is inherently undersized for this frequency band. This forces to opt for a non-resonant antenna design. A parallel approach is aiming at enhancing the near-field inductive potential of the antenna relative to the local magnetic field polarization at the antenna location. The integration of a tunable matching network, specifically designed to improve impedance matching between the antenna and the coaxial TL at more desired lower frequencies, is planned. Moreover, a non-resonant design is justified by the proven effectiveness of the current antenna in detecting plasma instabilities, despite its substantial impedance mismatch over the operational bandwidth. Such a mismatch has not prevented the system from performing well since 2022. A high signal-to-noise ratio of signals generated by RE is the most plausible explanation. Simulations have been performed using "*CST Studio Suite*" frequency domain solver and partially cross-checked with "*Ansys HFSS*". The first step of the simulation activity consisted in evaluating the e.m. properties of the current antenna system, taken as the reference scenario. Subsequently the eight antenna configurations shown in Figure 3 have been investigated: Back Feed (*BkF*), Bottom Feed (*BtmF*), Parallel Double Loop (*PDL*), Series Double Loop (*SDL*), Parallel Triple Loop (*PTL*), Shielded Loop (*SL*), Crossed Double Loop (*CDL*) and Crossed Triple Loop (*CTL*). In all cases, simulations reveal that a slight reduction in the gap between the antenna and the plasma enhances the wave coupling efficiency, being most of the RE signals under the cut-off frequency of the TCV port.

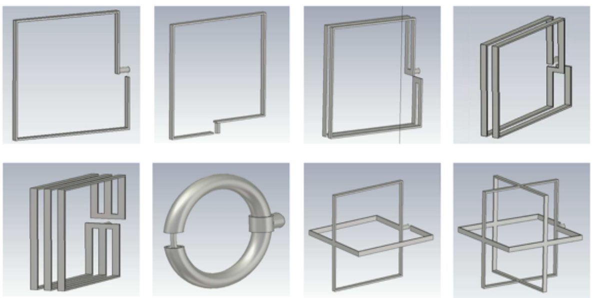

Fig. 3: sketches of the antenna designs investigated with CST. From the top-left to the bottom-right: BkF, BtmF, PDL, SDL, PTL, SL, CDL and CTL.

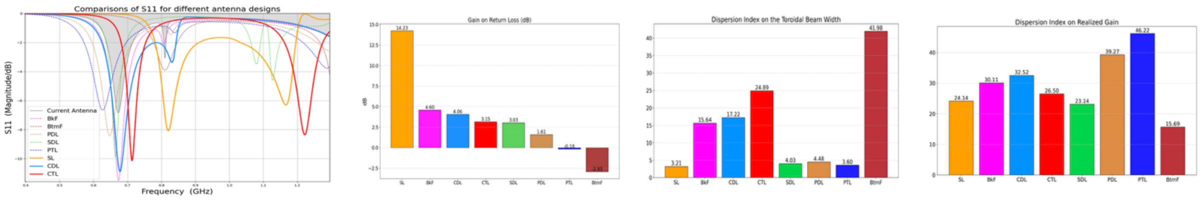

Fig. 4: the results of the CST analysis of the eight antennae under study in respect to parameters A), B), C) and D) described in the text are shown here above, respectively in panels a, b, c and d.

The installation of the antenna should thus be performed as close as possible to the plasma. An assessment aimed at qualifying the new designs is carried out comparing their features against a set of parameters, as shown in Figure 4: A) return loss $RL(freq) = 20\,log_{10}\Gamma$, where $\Gamma = |S_{11}|$ is the reflection coefficient; B) gain on *RL* at resonance with respect to the current loop antenna; C) dispersion index (*D.I.*) of the antenna toroidal beam width (BW) evaluated at -3 dB power level relative to the tokamak radial direction, where $D.I.(X) = |\sigma[X(freq)]^2/AVG[X(freq)]|$; D) *D.I.* of the realized antenna gain evaluated in the tokamak radial direction, where $G_{realized} = 4\pi\,(dP_{rad}/d\Omega)/P_{stimulated}$; E) $G_{realized}$ evaluated in the tokamak radial direction.

Conclusions. An improvement is underway on the TCV RF antenna, for enhancing the capabilities to detect RE-driven instabilities and testing measurements of low frequency range daughter waves by low ECH power threshold PDI. The DAS has already been upgraded, while a new antenna design is currently under development, with some configurations (*CTL*, *SL*, *SDL*) appearing to be the most promising. The antenna selected as the best candidate from the analysis will be built and installed in the TCV vessel between 2025 and 2026.

Acknowledgements. *This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 - EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.*

The authors would like to thank A. Guercio, C. Allocchio, E. Sanvito, E. Grüter, L. Gentili and A. Di Bastiano for their valuable support of our scientific work.

References

[1] *P. Buratti et al., Plasma Phys. Control. Fusion* ***63*** *095007 (2021)*
[2] *W. Bin et al., Phys. Rev. Lett.* ***129*** *045002 (2022)*
[3] *W. Bin et al., Rev. Sci. Instrum.* ***93*** *093516 (2022)*
[4] *E. Z. Gusakov and A. Yu. Popov, Phys. Plasmas* ***23*** *082503 (2016)*
[5] *A. Clod et al., Phys. Rev. Lett.* ***132*** *135101 (2024)*
[6] *C. Castaldo et al., Nucl. Fusion* ***64*** *086003 (2024)*
[7] *M. Ono, Phys. Fluids B* ***5*** *241 (1993)*