Experimental Investigations of Runaway-Electron-Driven Instabilities in Tokamaks

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Outline

- **Introduction**: runaway electrons (RE) and instabilities in tokamaks

- **A few examples of what can be measured in tokamak plasmas:**

  - *Some results from the Frascati Tokamak Upgrade (**FTU**)*

  - *Some results from the Tokamak à Configuration Variable (**TCV**)*

- **Conclusions**

Runaway Electrons and KI in Tokamak Plasmas

Runaway Electrons (RE) are electrons accelerated (up to become relativistic) when the accelerating electric field in a tokamak exceeds collisional drag → at disruptions (**high electric field**) and at the plasma startup (**very low density**).

Above a critical electric field they undergo **exponential growth**

RE are a great concern for fusion devices since they can cause severe damages → **control and mitigation strategies are a key issue**.

RE can **drive kinetic instabilities and excite EM waves**, which, in turn:

1- **scatter RE** in momentum space;

2- enhance pitch-angle scattering, leading to larger synchrotron losses → **lower RE energy**;

3- **raise critical electric field** for RE formation.

Role of instabilities is beneficial

$$\omega - k_{\parallel} v \cos\theta - k_{\perp} v_d = n \frac{\Omega_{ce}}{\gamma}$$

$n = 1$, cyclotron Doppler

$n = 0$, Landau (Cherenkov) resonance

$n = -1$, anomalous Doppler (ADI)

θ, (pitch) angle between **B** and $\boldsymbol{v}$

$k_{\perp} v_d$, drift correction → <u>often neglected</u>

Some Results from Instability Studies at *Frascati Tokamak Upgrade (FTU)*

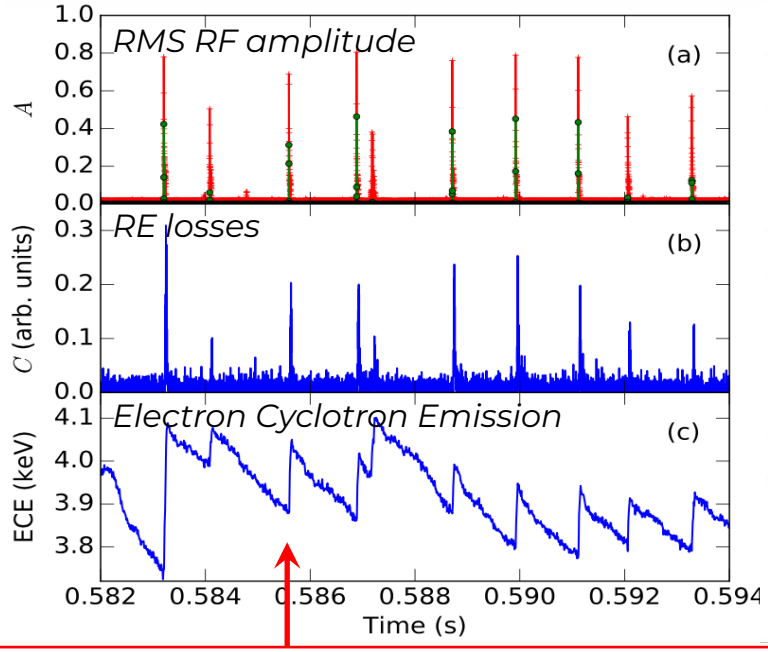
2018 - 2019

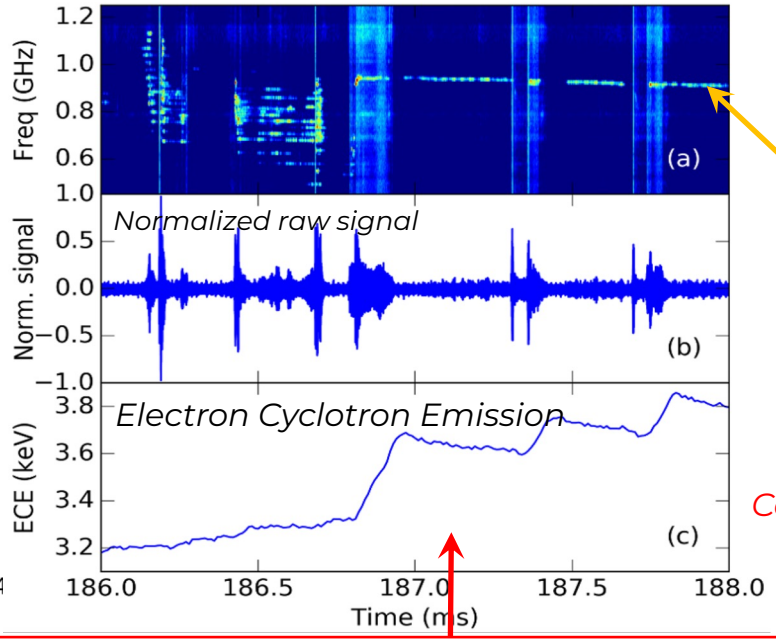
Intermittent Bursty Dynamics

A simple antenna setup was employed at FTU **to test RF detection of signals from instabilities**:

ex-vessel antennas + high quality cables + 8-bit NI PXIe digitizer

Wideband bursts and emissions: they are detected practically every time when even low-energy seed RE populations are formed.



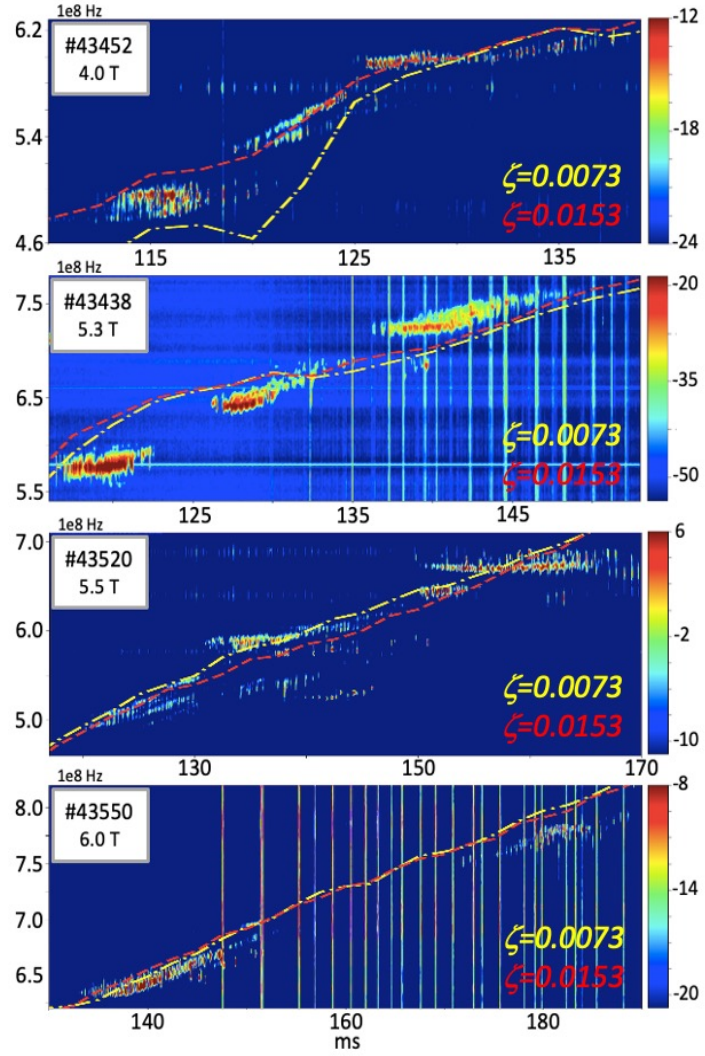


Possibly **Cherenkov** interaction

*P. Buratti et al., Plasma Phys. Control. Fusion **63** 095007 (2021)*

Suprathermal ECE consistent with RE pitch-angle scattering → **Anomalous Doppler**

Nearly Monochromatic Wave Families



We also observed a large number of coherent wave families:

Lower Hybrid Waves

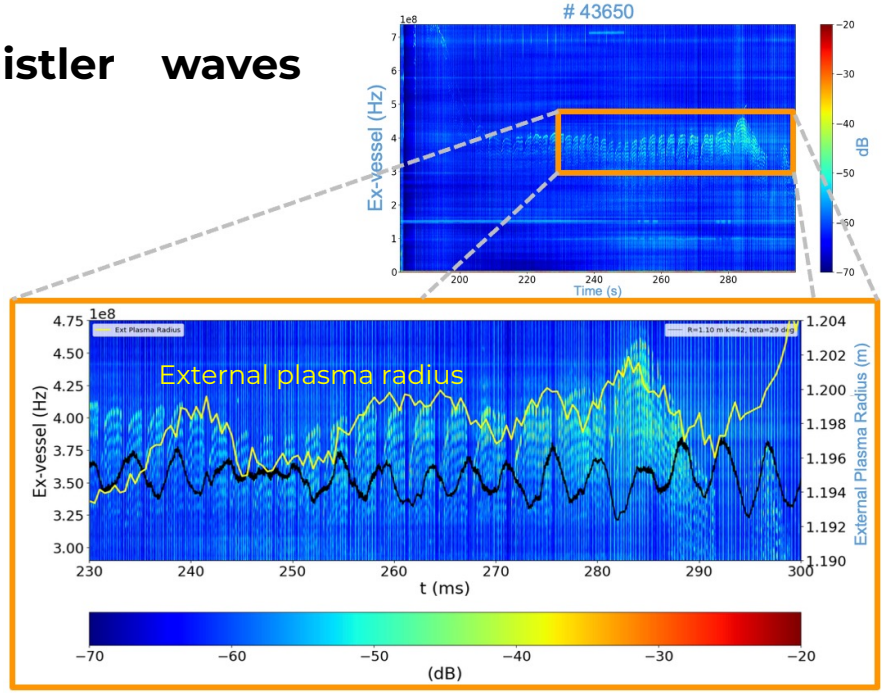
In 2022 we reported **the first observation of RE-driven Lower Hybrid Waves** (LHWs) in a tokamak plasma.

W. Bin et al., Phys. Rev. Lett. ***129*** *045002 (2022)*

Whistler Waves

Indications of **Whistler waves** were also found

W. Bin et al., ECPD (2023)



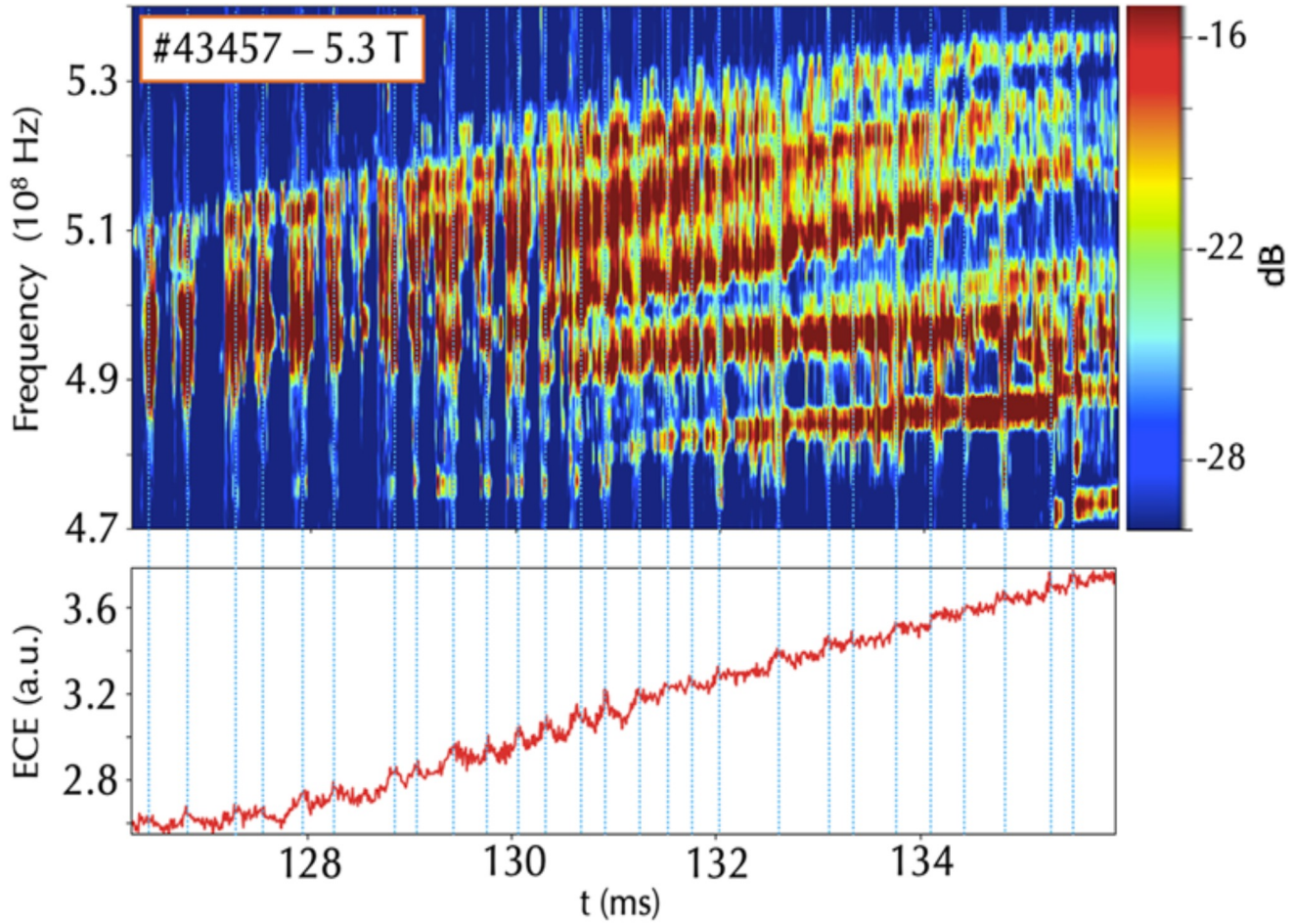
Black line:
Whistler dispersion relation, calculated for k=42 and ϑ=29°

LHWs are also invoked to explain Galactic "Fermi bubbles" *A. Cardinali et al., ApJ* ***995*** *63(2025)*

Diagnostic Potential of RF Measurements

Experiments show that **even weakly energetic seed RE at an early stage of formation** are readily **associated with clearly detectable instabilities** in the RF range

W. Bin et al., Rev. Sci. Instrum. ***93*** *093516 (2022)*

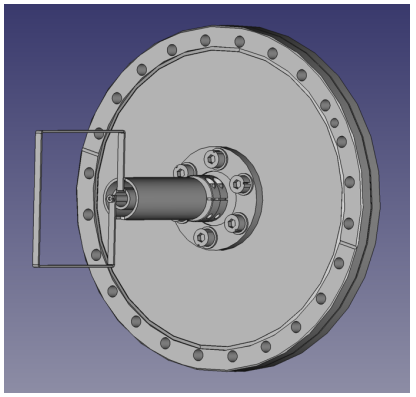


Some Results from Instability Studies at *Tokamak à Configuration Variable (TCV)*

2021 - present

New Classes of RE-Driven Instabilities

In 2021 we proposed RE-driven waves experiments at *TCV* (Lausanne). We designed and installed a single loop in-vessel antenna.

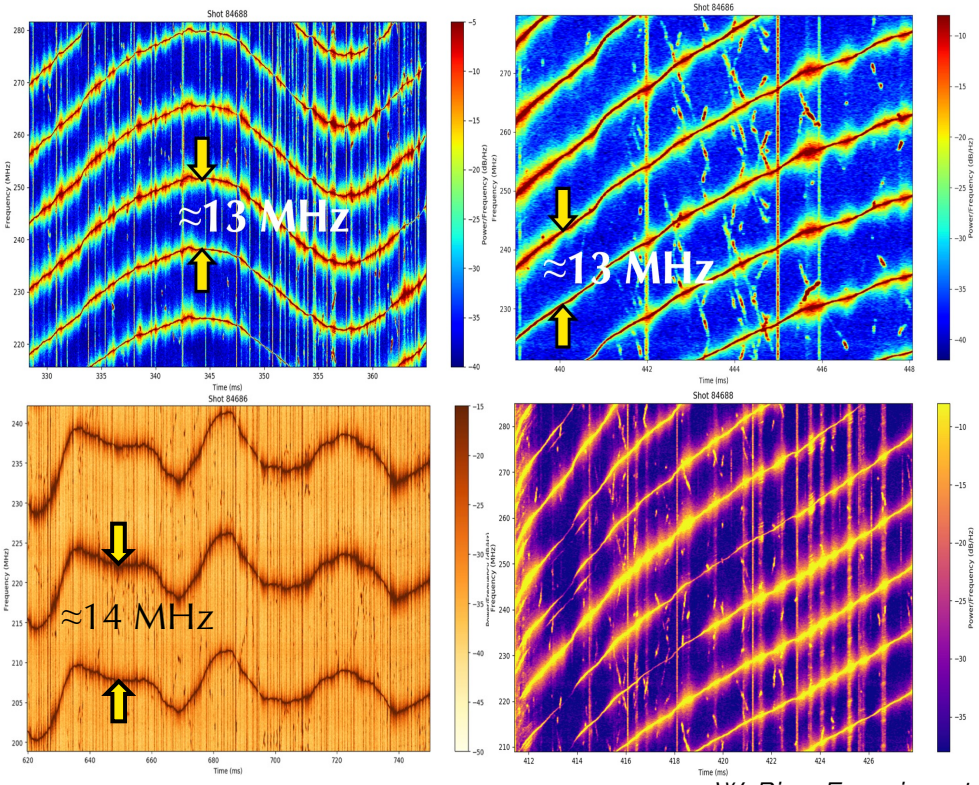


New Branches of Waves Emerge in TCV Scenarios

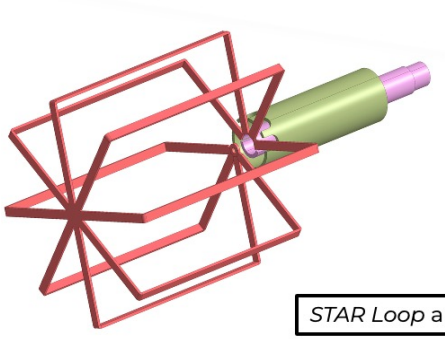
Ion cyclotron frequency ≈ 11 MHz → wave frequency spacing is ≈ 13-14 MHz

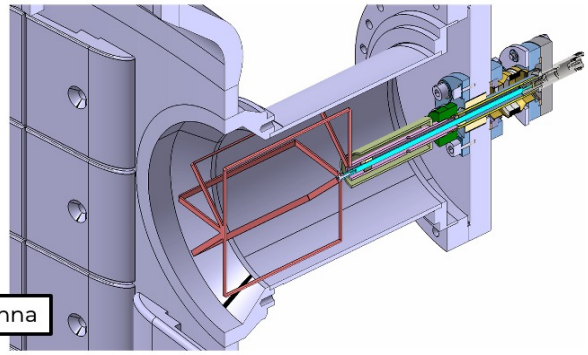
Results are consistent with a recently developed hot plasma model in:

*C. Castaldo et al., Nucl. Fusion **64** 086003 (2024)*



In 2024 an EUROfusion grant was secured for the re-design of the current single-loop system → the new antenna is currently under construction and installation is foreseen before the end of 2026.

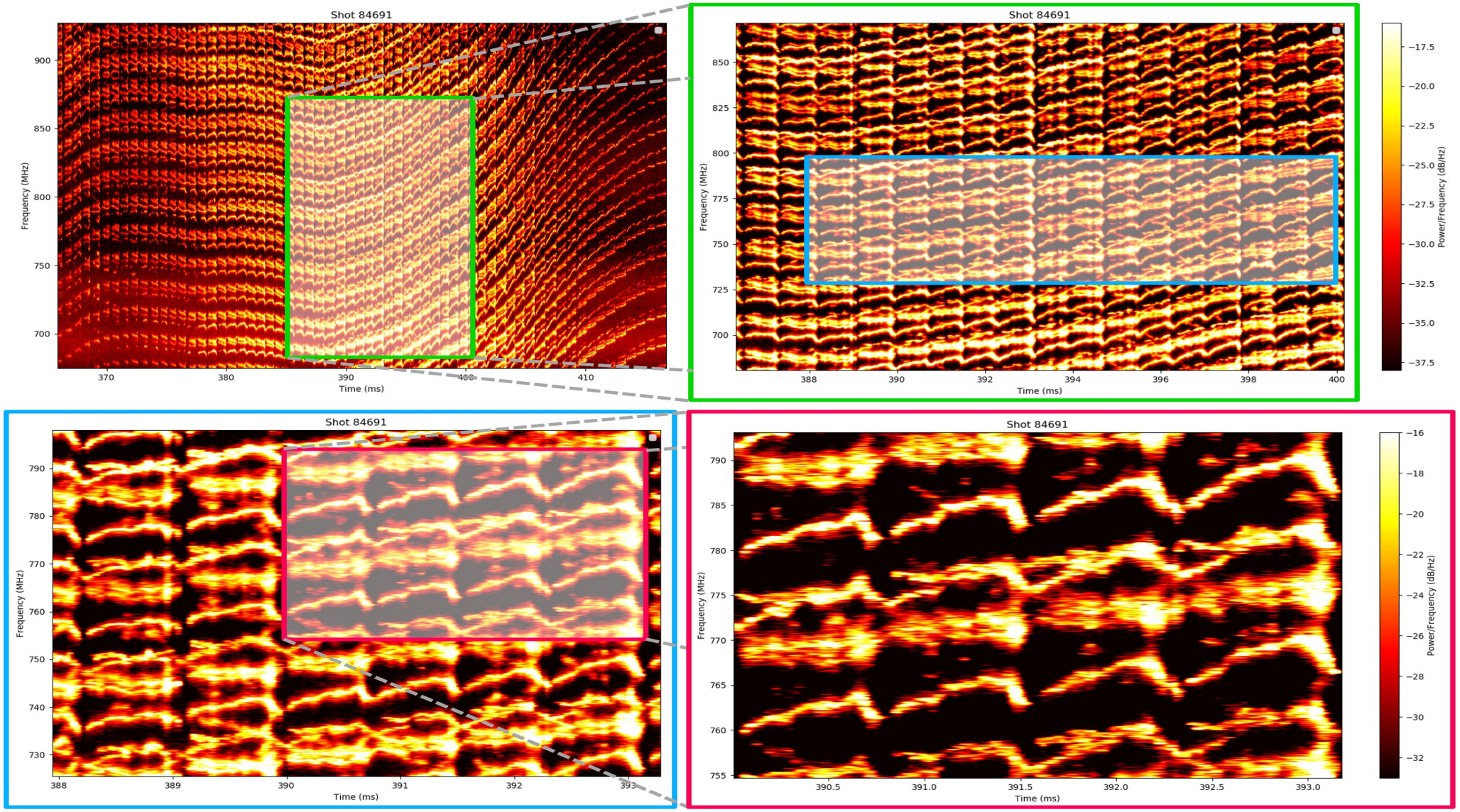




STAR Loop antenna

RF Technique Offers Exceptional Sensitivity

W. Bin et al., EPS (2025)



Conclusions

The results obtained from the RE-driven KI activities conducted over the past years in different tokamak plasmas have demonstrated that:

1- Kinetic instabilities turn out to be **an intrinsic feature of nearly all RE scenarios** in tokamaks.

2- **RF radiation**, originating from unstable plasma waves coupling, **carries a large amount of** detailed **information** on the dynamics of the instabilities and RE, otherwise not accessible using other diagnostics.

3- In tokamak plasmas, kinetic **instabilities are already driven during the very early formation phase** of still low-energy seed RE populations (and not only during later more energetic phases, such as the current flat-top or the plasma disruptions):

→ measuring RF signals is a **diagnostic tool to monitor the build-up phase** of seed RE populations, when the capabilities of most diagnostics are still very limited.

4- **EM wave detection is a highly sensitive technique** capable of identifying even very weak instabilities, thus again reaffirming its value for diagnostic applications.

Thank You !