KSTAR wave detection (Yun)

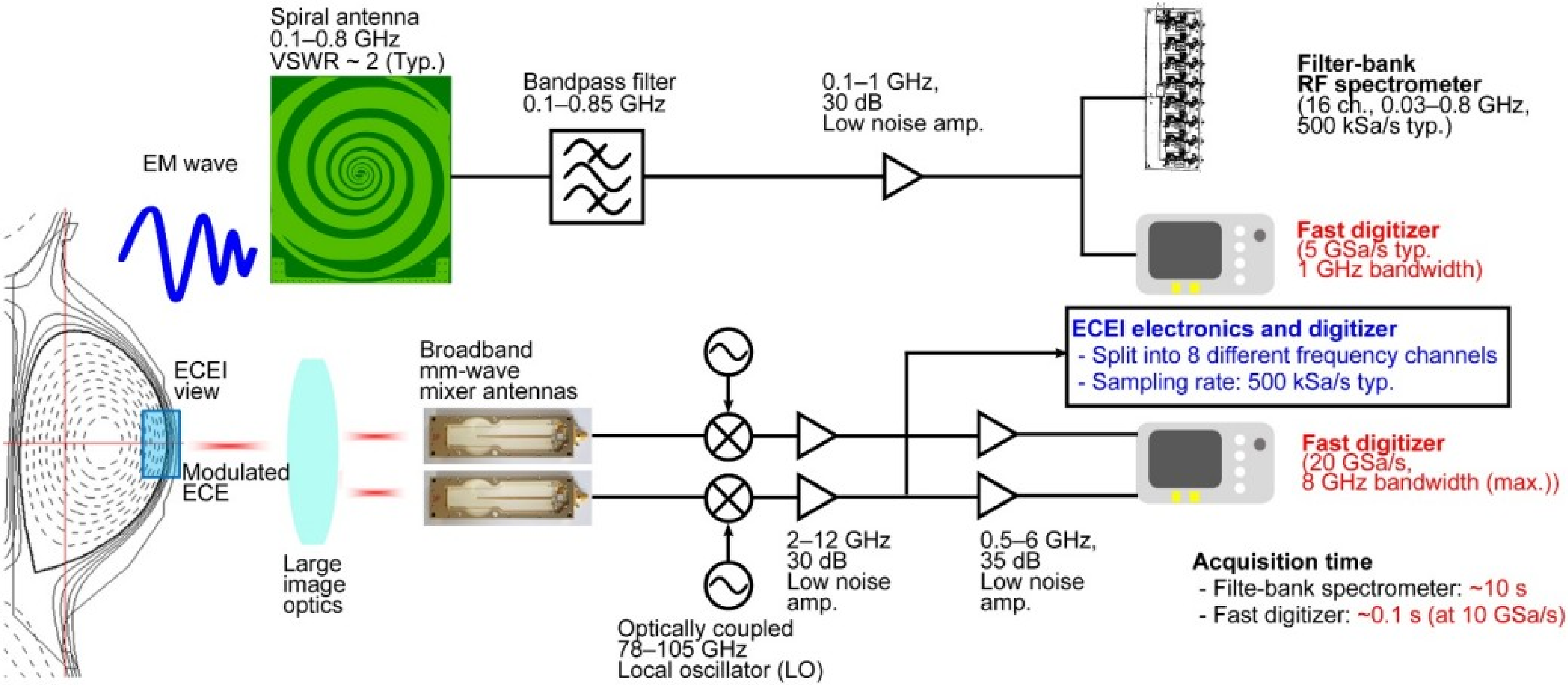


Figure 1. Schematic of RF diagnostic system. Two different types of antennas, spiral and mm-wave antenna mixers, are installed on the KSTAR tokamak. The mm-wave mixer antennas utilize the detector of ECE imaging system [31].

Wave detection

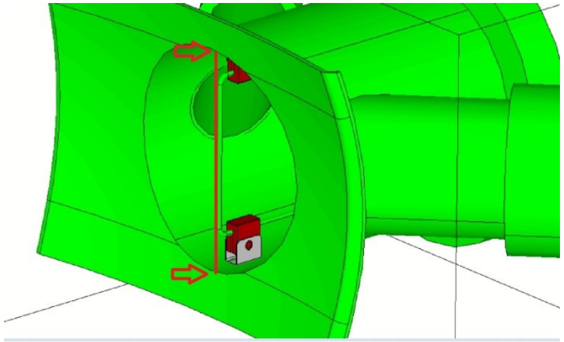
- Wideband (log-periodic) antenna placed *outside* the vacuum vessel, in front of the exit of a vertical port closed by a dielectric window.

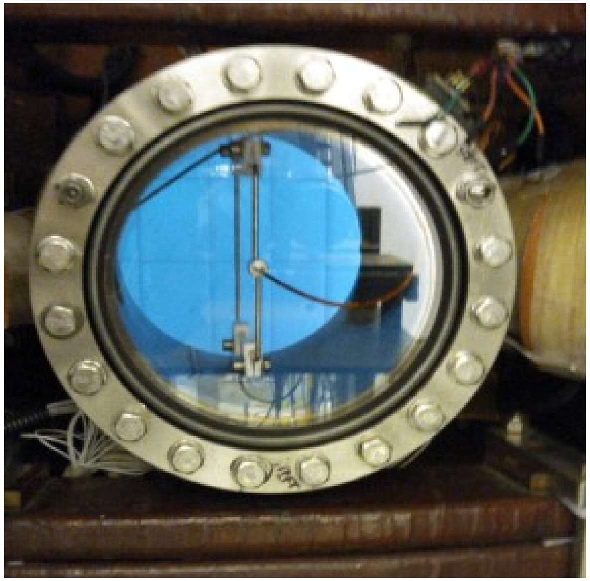
NI PXIe-5186   8 bit resolution
12.5 Gs/s max. sampling rate

- Antenna signal acquired by NI PXIe-5186 fast digitizer.
- ~400 MHz cutoff due to propagation in the port.

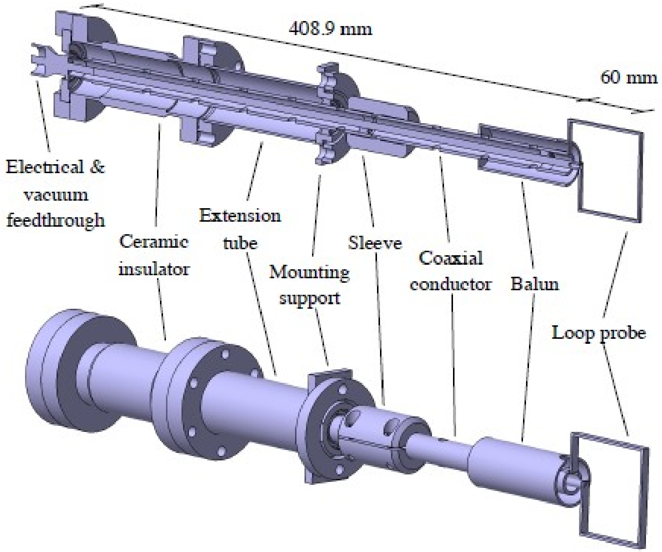
In-vessel antennas to avoid cutoff

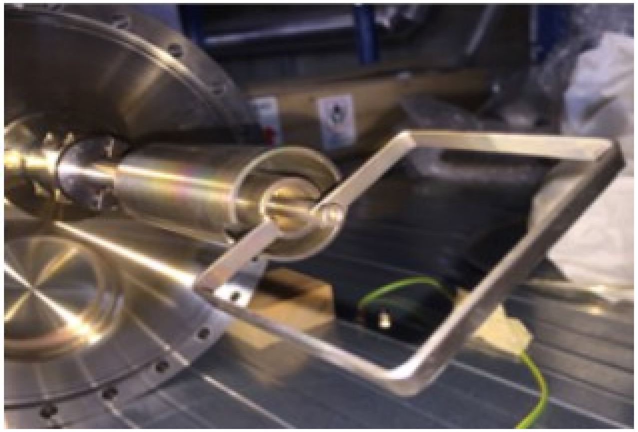
COMPASS - Dec. 2020
Also 500 MHz wave injection





TCV - Ongoing





KSTAR wave detection

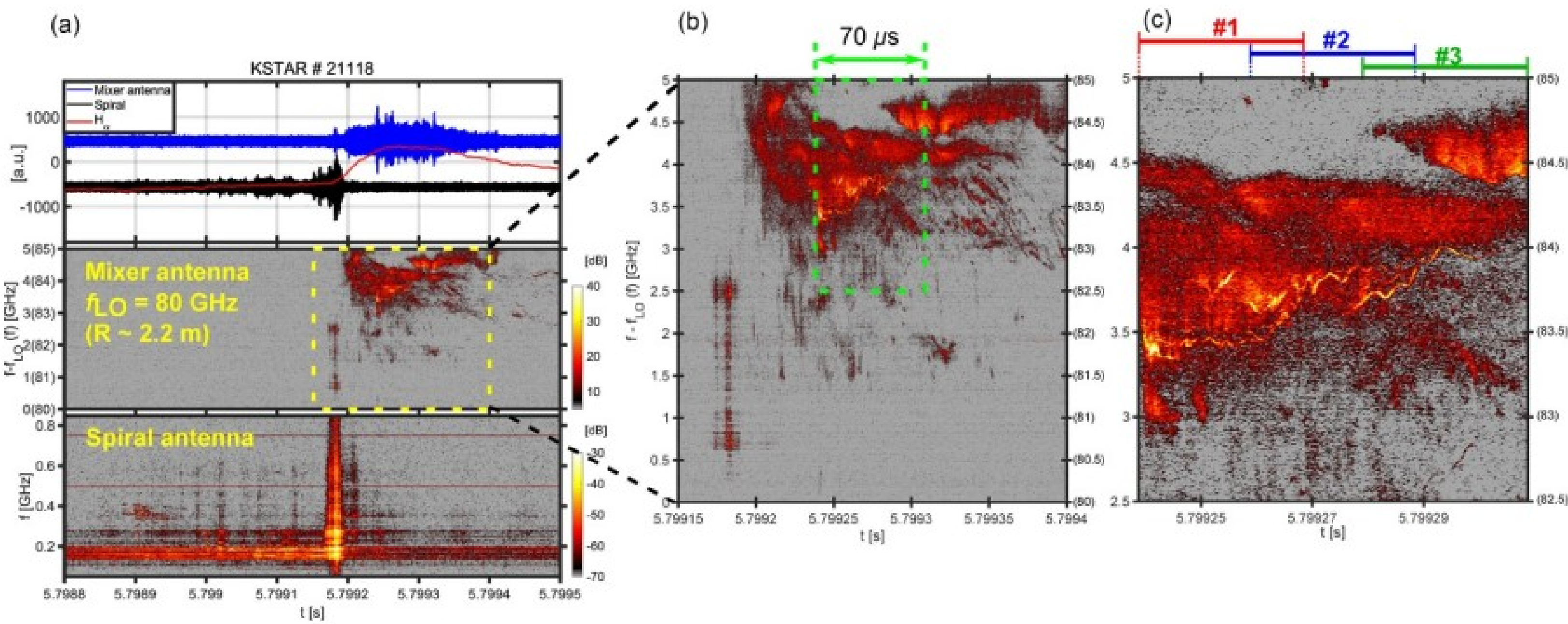


Figure 2. An example of RF emissions at the pedestal collapse in KSTAR #21 118. (*a*) Time trace of mm-wave mixer antenna, spiral antenna (10 GSa s^{-1}), H_α, mixer antenna signal spectrogram, and a spiral antenna signal spectrogram. (*b*) Magnified spectrogram of the mm-mixer antenna signal. The vertical labels simultaneously show the IF frequencies on the left and the ECE frequencies on the right. (*c*) Magnified images of long-lasting falling-tone in figure 2(*b*). The labels (#1–#3) indicate the three distinct stages of dynamic features of narrowband emissions. The colormap of figures 2(*b*) and (*c*) is the same as the middle panel of figure 2(*a*).

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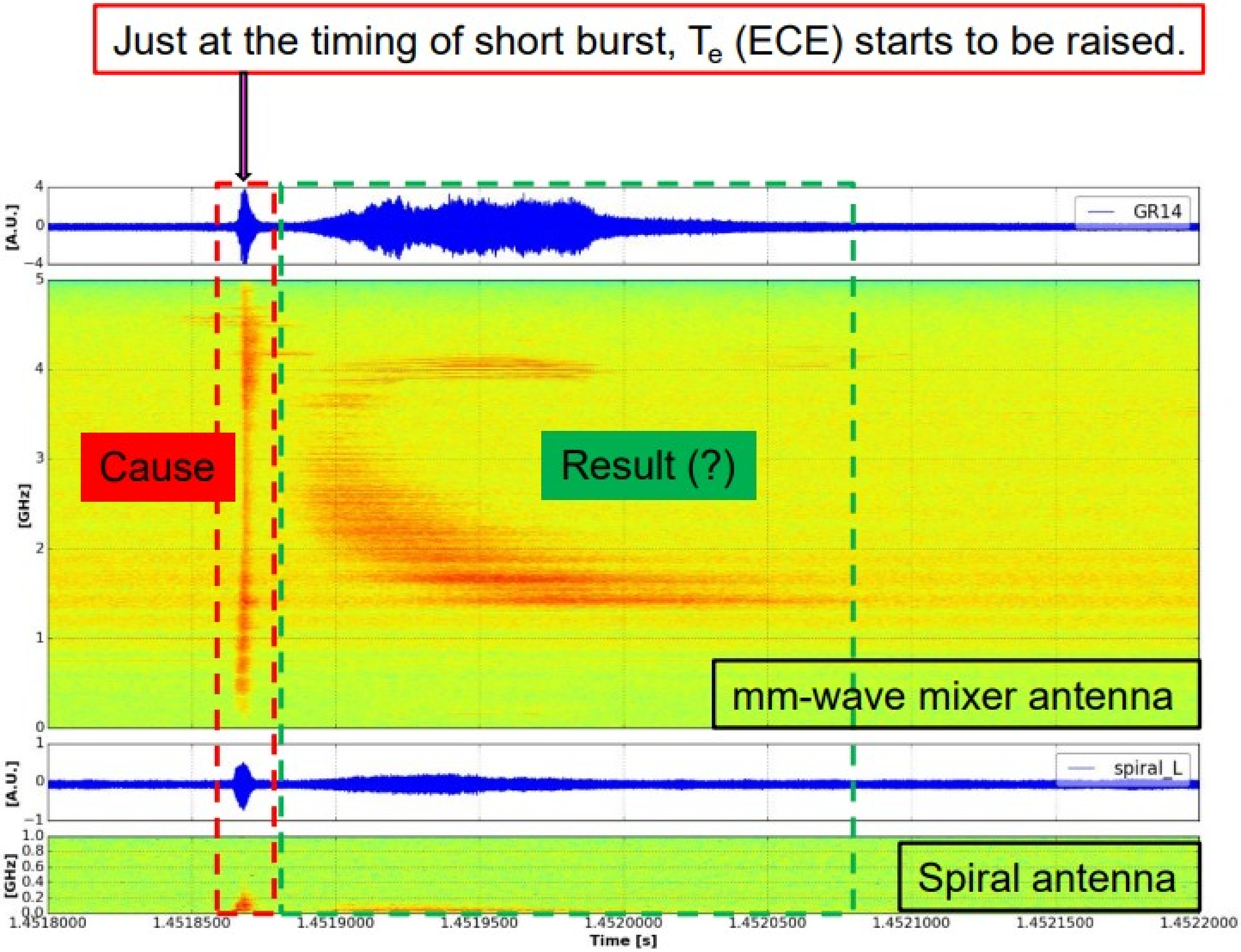
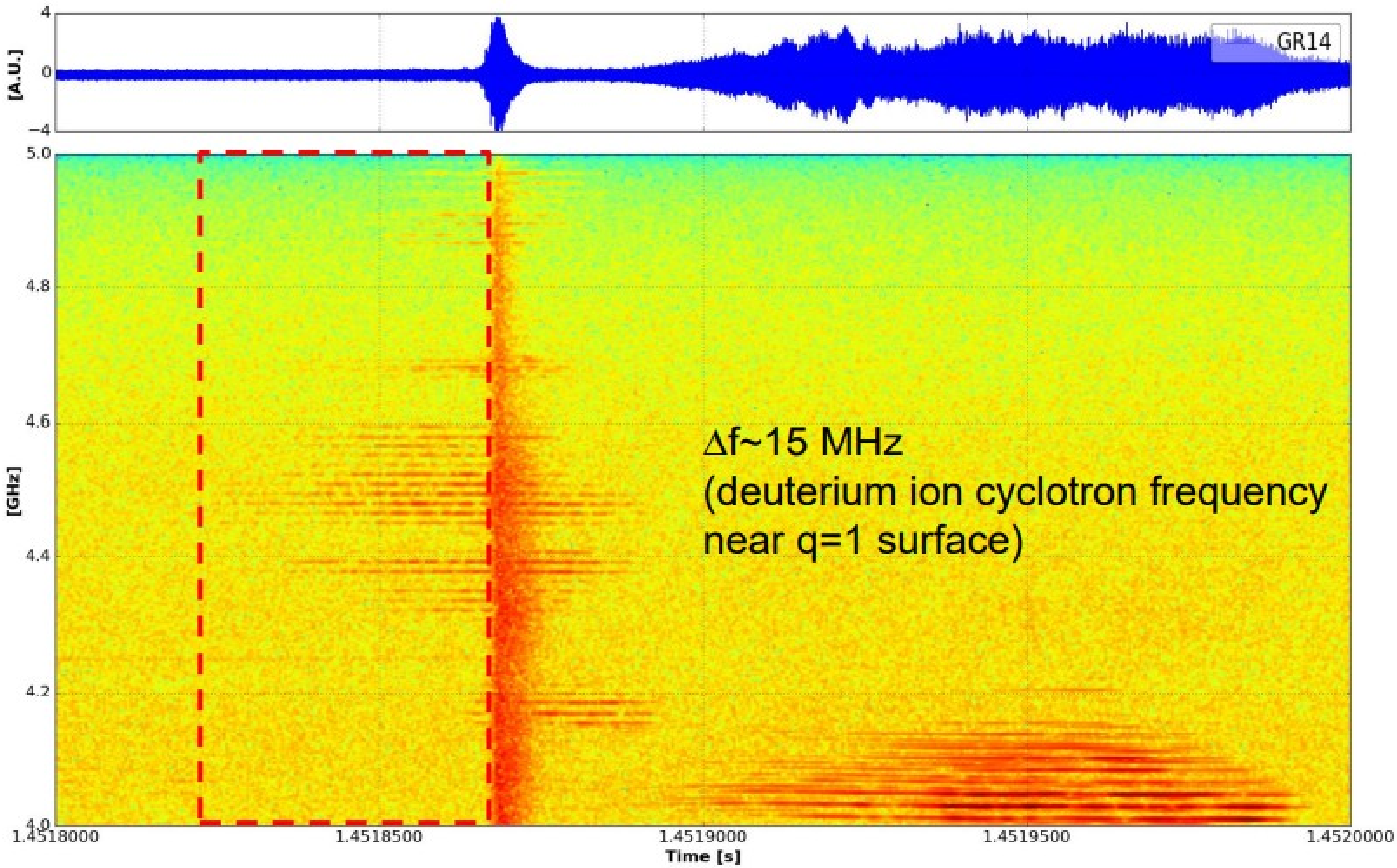
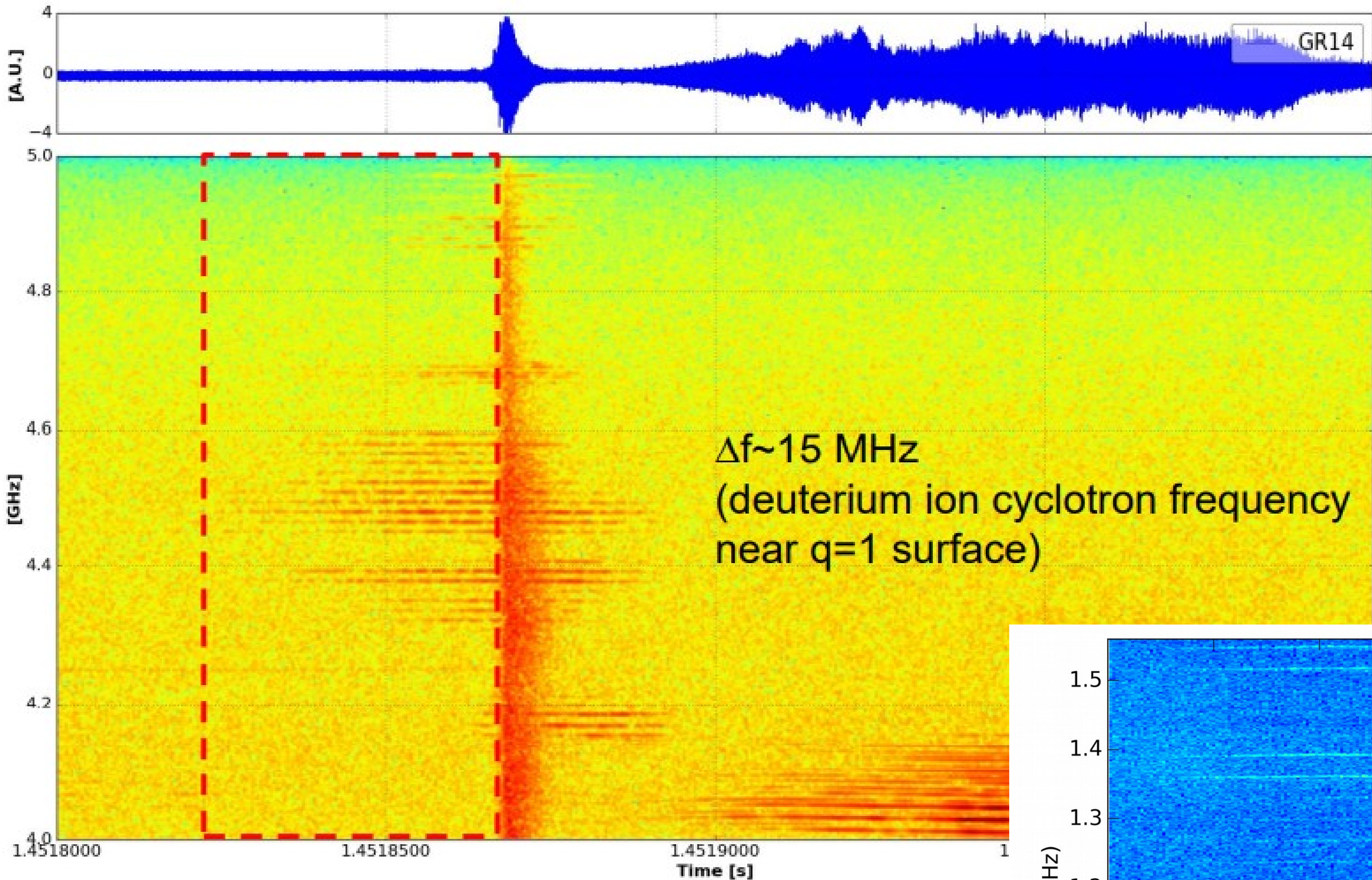
KSTAR wave detection



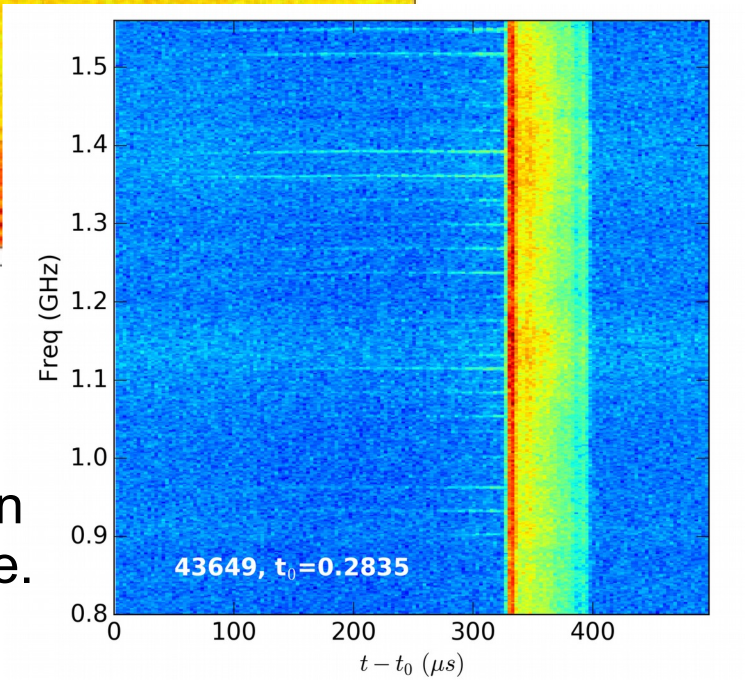
KSTAR wave detection



KSTAR vs FTU wave detection

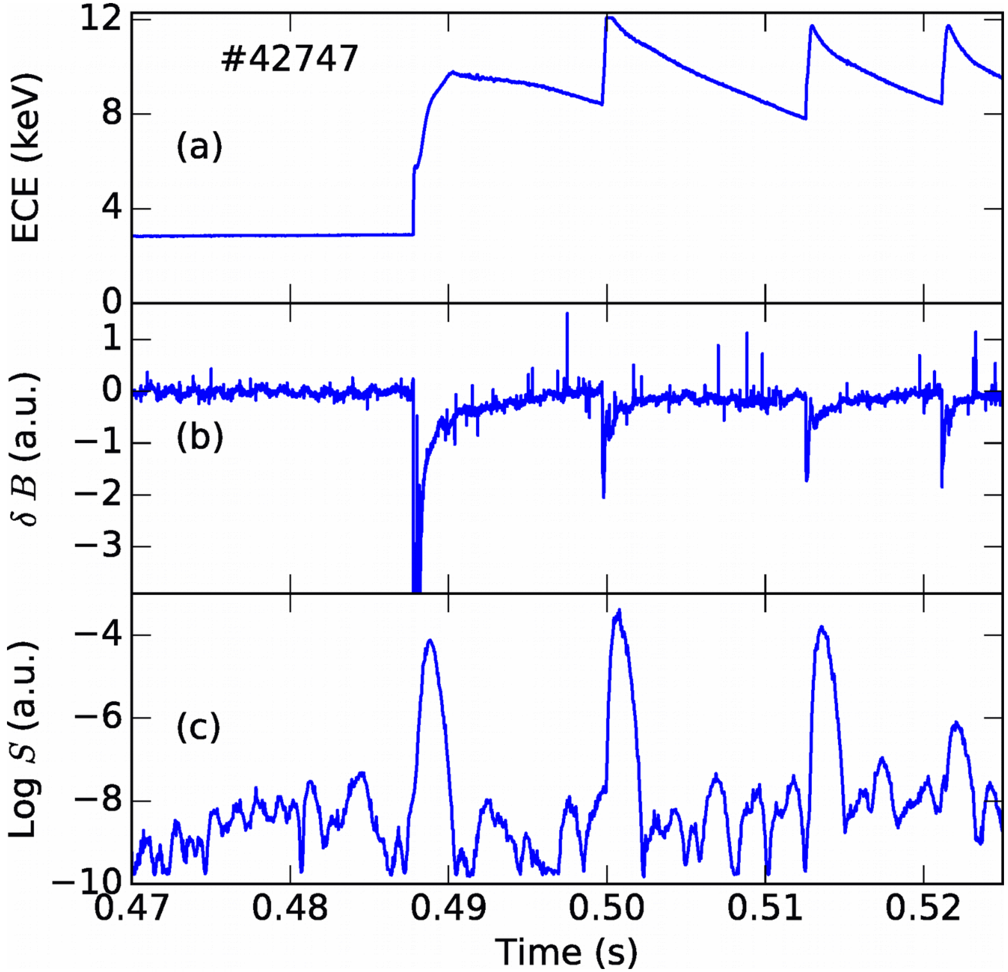


31 MHz = ion cyclotron frequency at LFS edge.



ECE spikes (Korsholm report)

- Danger for microwave diagnostics
- Data available from FTU to integrate ITPA studies



- ECE radiation temperature at 370 GHz
- Mirnov coil signal, showing macroscopic prturbations; the first spike is out of scale.
- Radio emission at 500 MHz, as measured by an analog spectrum analyzer.

RE detection by soft x-ray in MST (Delgado)

- Early detection at low energies (too late with hard x)
- multi-energy soft x-ray pinhole camera 2-5.5 keV
- Interest for the current rise phase
- Hollow RE beam at formation

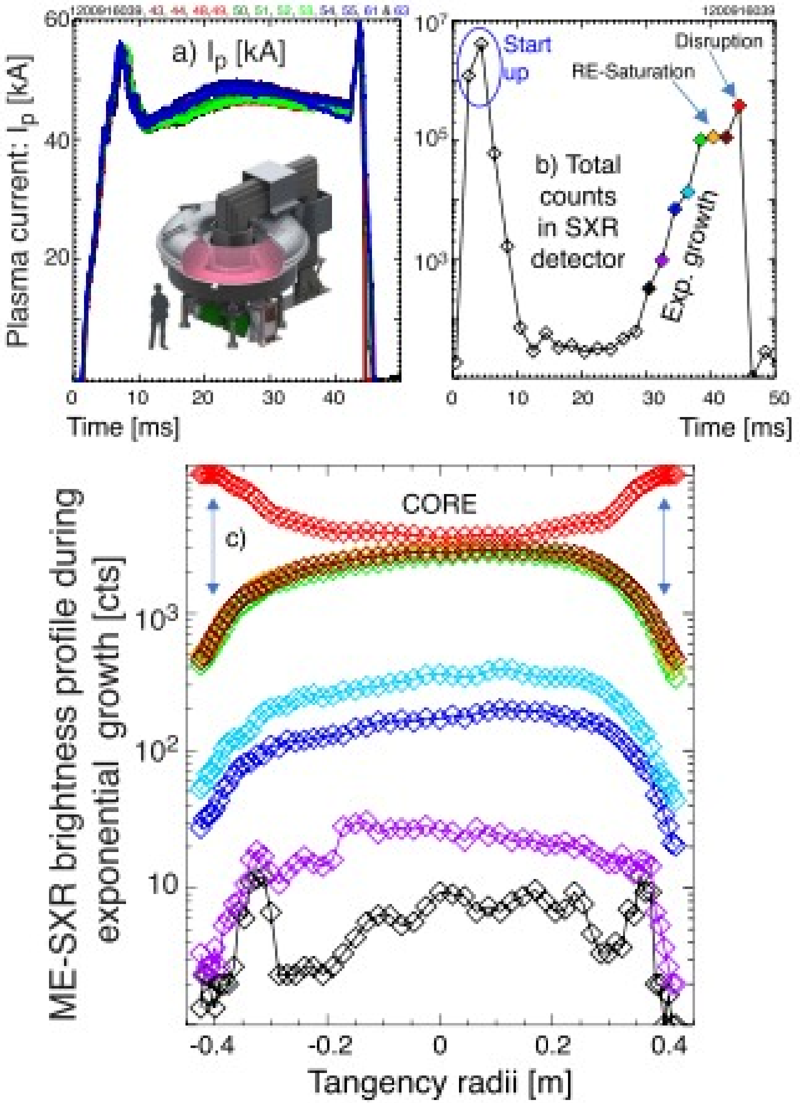


FIG. 9. (a) Tokamak I_p traces for reproducible discharges. The time-history of the total number of counts on the detector during a typical "shot" is depicted in (b) while the time evolution of the spatially resolved profiles during the RE exponential growth and disruption is shown in (c).

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Italian National Agency for New Technologies, Energy and Sustainable Economic Development

40th Meeting of the ITPA Topical Group on Diagnostics 25 - 28 October 2021

Detection of RF emission by runaway electrons

- *CNR, ENEA, University of Tor Vergata:*
- W. Bin, P. Buratti, A. Cardinali, D. Carnevale, C. Castaldo,
- O. D'arcangelo, F. Napoli, A. Selce
- *IPP-CAS:*
- J. Cerovsky, O. Ficker, M. Jerab, E. Macusova
- *SPC:*
- M. Gospodarczyk, U. Sheikh

Presented by P. Buratti

Motivation and questions

- Generation of runaway electron (RE) beams is a **machine safety** issue for ITER
- RE beams can be generated
  - at disruptions (high electric field)
  - or at plasma startup (low density)

Motivation and questions

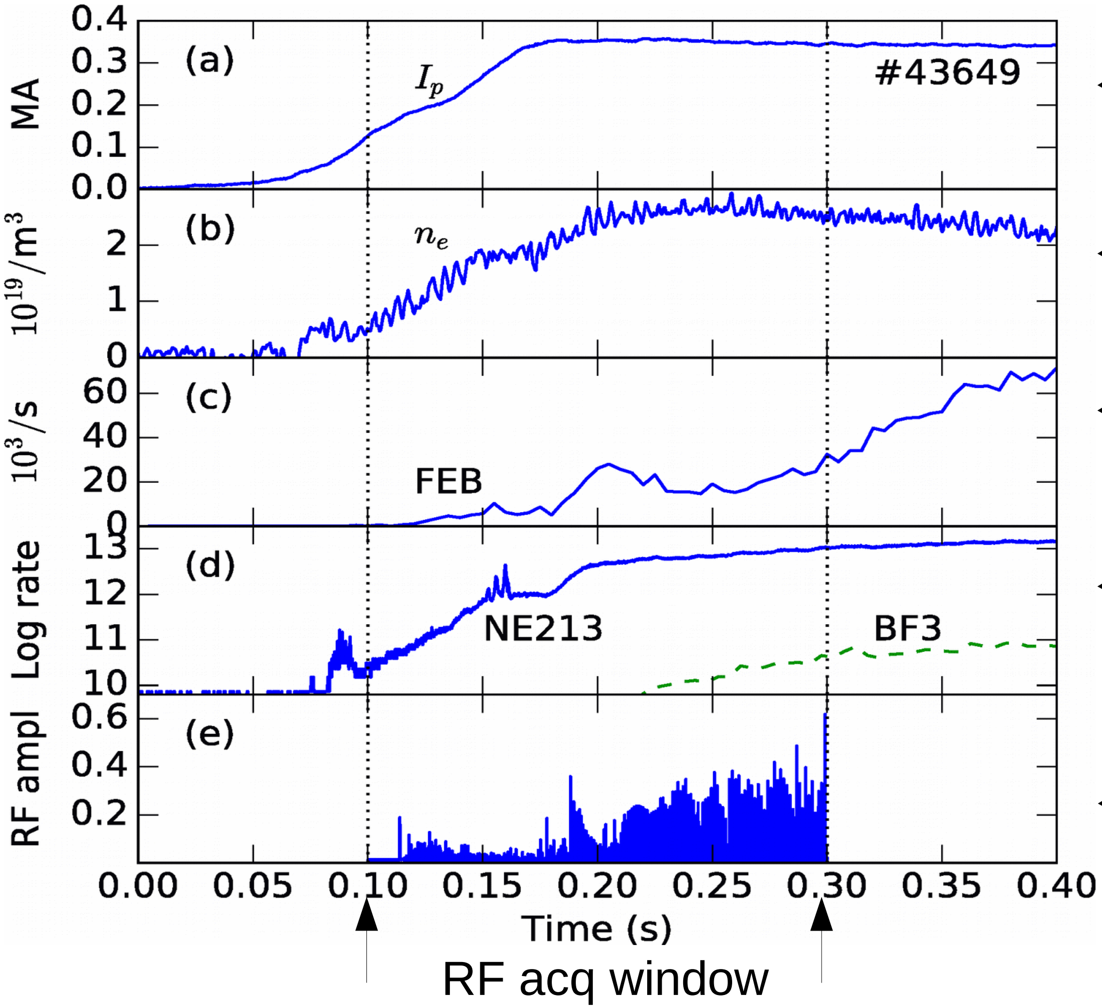
- Generation of runaway electron (RE) beams is a **machine safety** issue for ITER
- RE beams can be generated
  - at disruptions (high electric field)
  - or at plasma startup (low density)

- Is runaway electron (RE) dynamics entirely determined by Dreicer acceleration + avalanche + synchrotron losses?
- Or are there additional energy and momentum losses due to collective interactions with the bulk plasma?
- Can we *detect* and *characterize* plasma waves that mediate RE-bulk interactions?

- In the following: results from FTU, TCV and COMPASS

Smoking gun for RE-wave interactions (FTU)

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

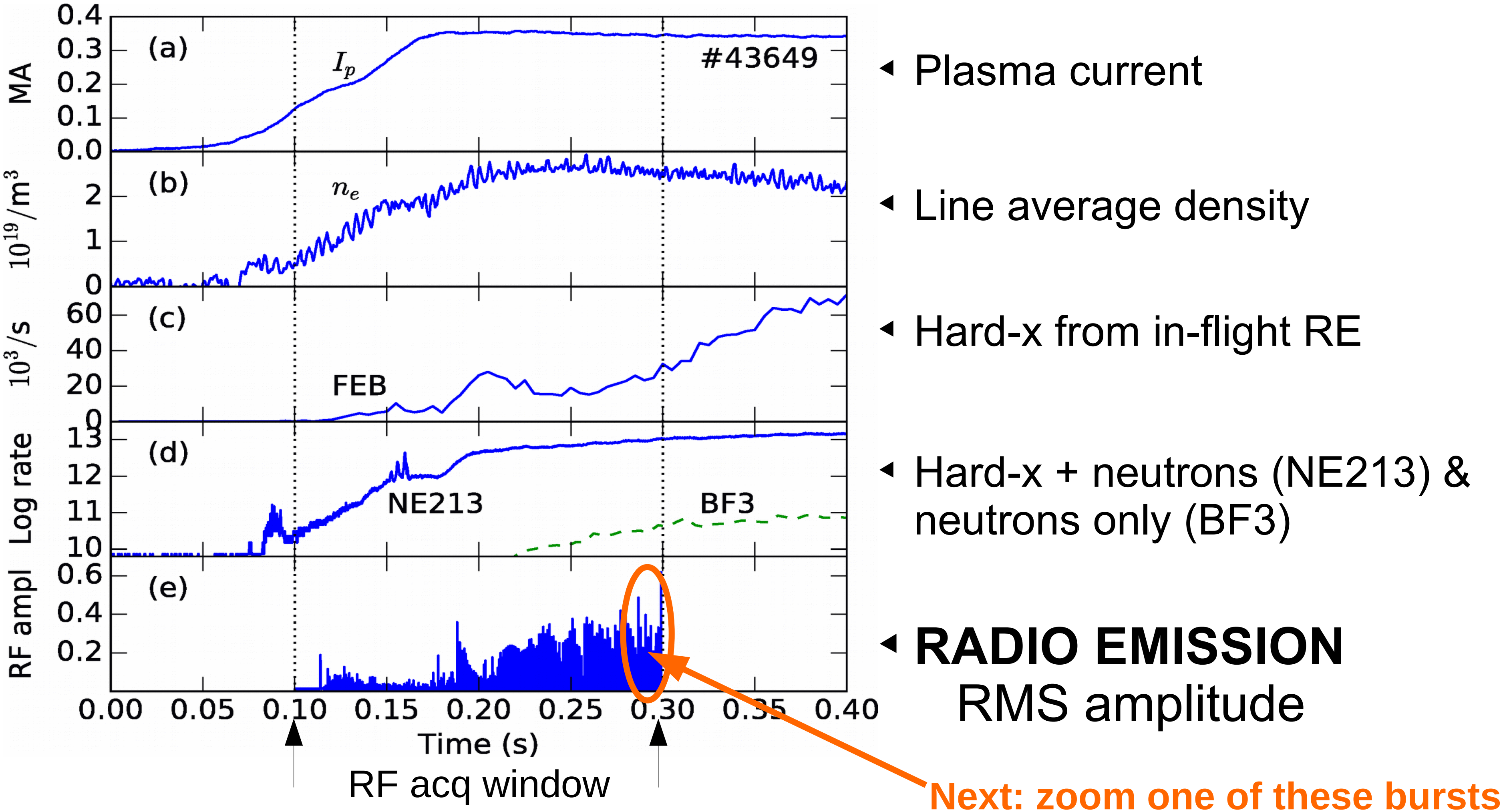


- Plasma current
- Line average density
- Hard-x from in-flight RE
- Hard-x + neutrons (NE213) & neutrons only (BF3)
- **RADIO EMISSION** RMS amplitude

- Bursty instabilities affect RE already in the formation phase
- RF detection is the most sensitive diagnostic for such instabilities

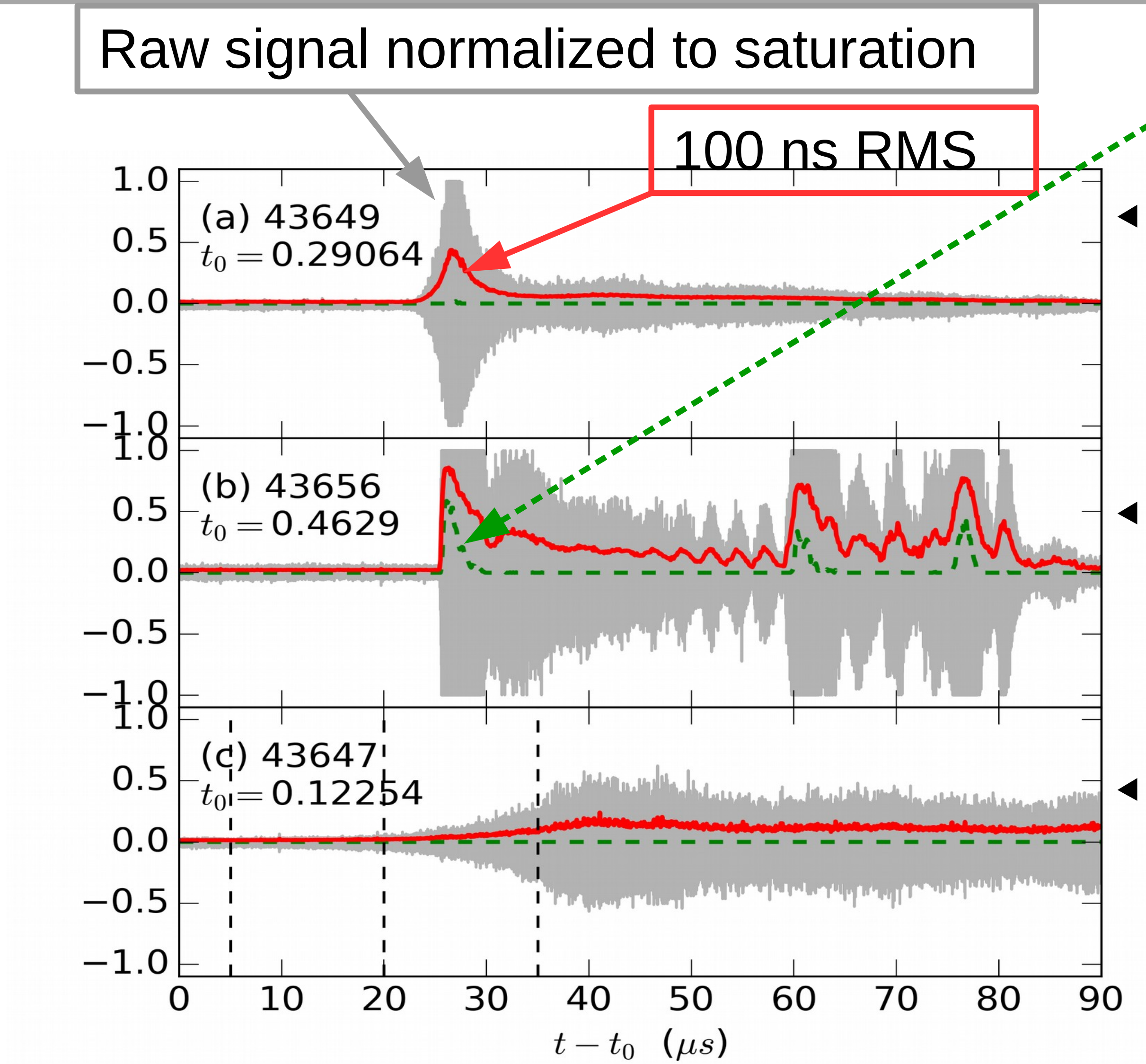
Smoking gun for RE-wave interactions

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



- Bursty instabilities affect RE already in the formation phase
- RF detection is the most sensitive diagnostic for such instabilities

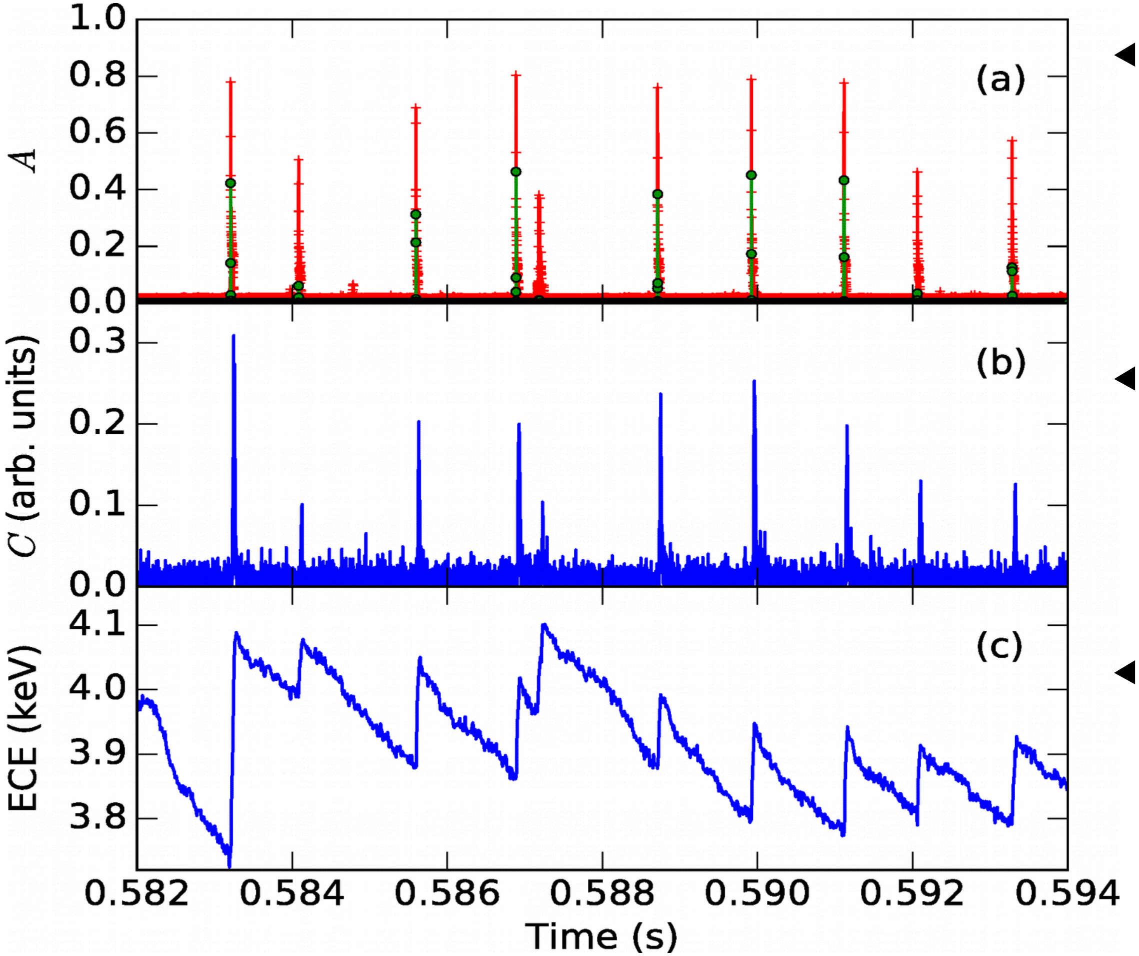
Wave burst structure



- Mild RE population: exponential front end with $1.1 \times 10^6\ s^{-1}$ growth rate
- Substantial RE: very sharp; complex tail
- Weak RE: much slower growth rate $\sim 10^5\ s^{-1}$

Spot out qualitative features and measure instability growth rate

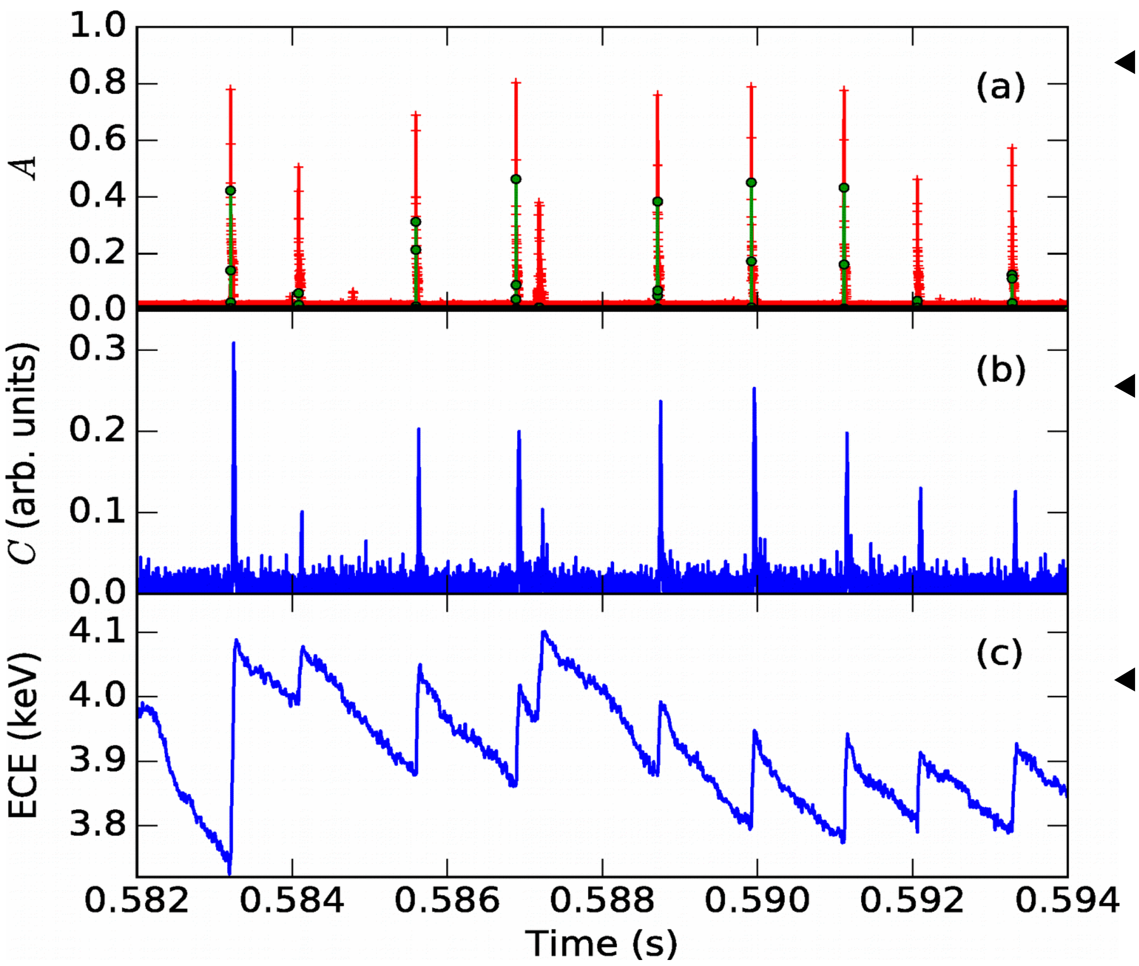
Integration of diagnostic data



- RMS RF amplitude (red) and fraction of saturated data (green).
- Cherenkov probe signal showing RE losses
- Suprathermal ECE showing RE pitch-angle scattering

- Identify RF bursts as signs of anomalous Doppler instabilities

Integration of diagnostic data



- RMS RF amplitude (red) and fraction of saturated data (green).
- Cherenkov probe signal showing RE losses
- Suprathermal ECE showing RE pitch-angle scattering

- Identify RF bursts as signs of anomalous Doppler instabilities
- ADI enhance by x2-x3 the critical *E*-field for RE avalanche

D. Carnevale et al 2021 Nucl. Fusion **61** 116050

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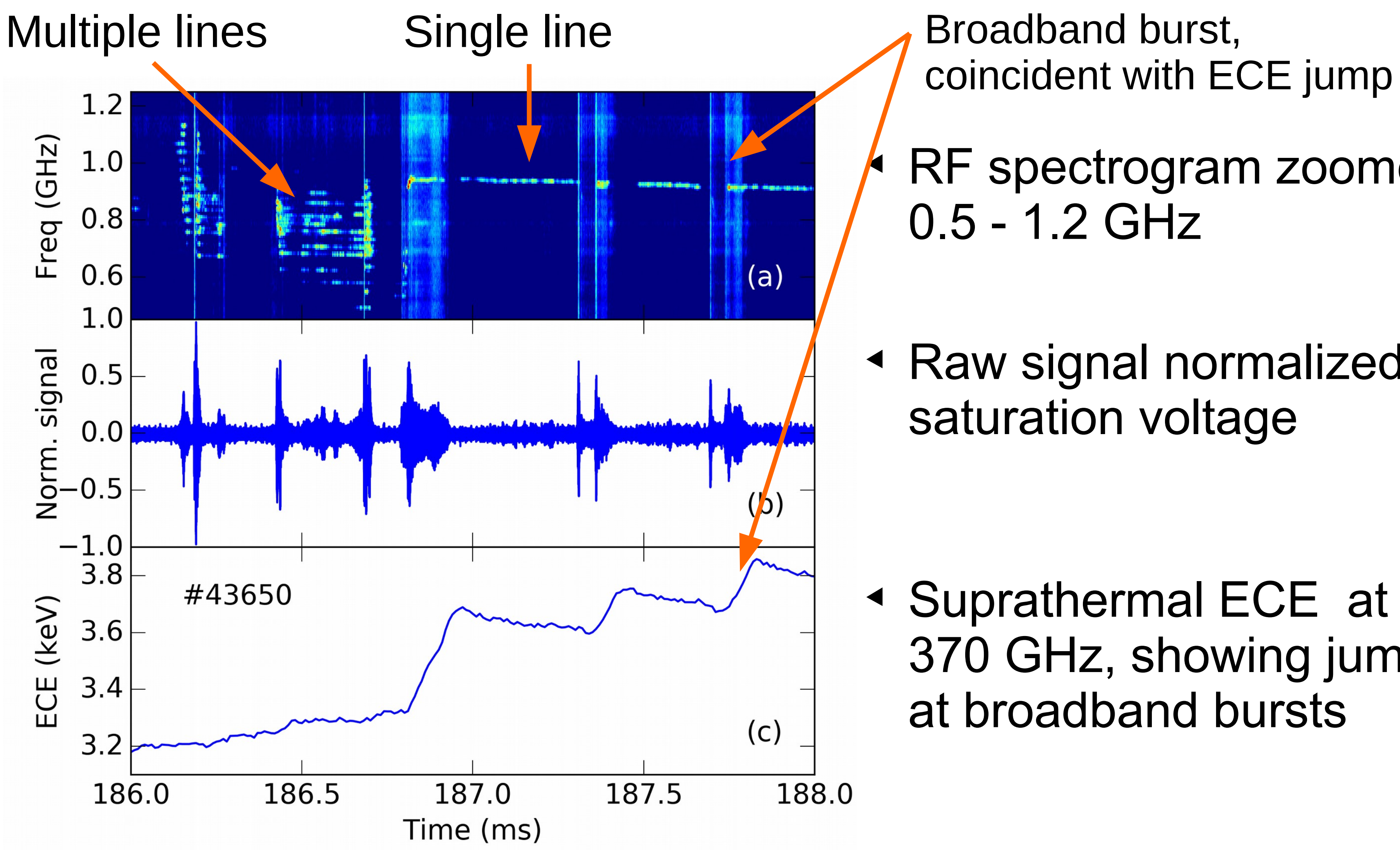
Spectral analysis

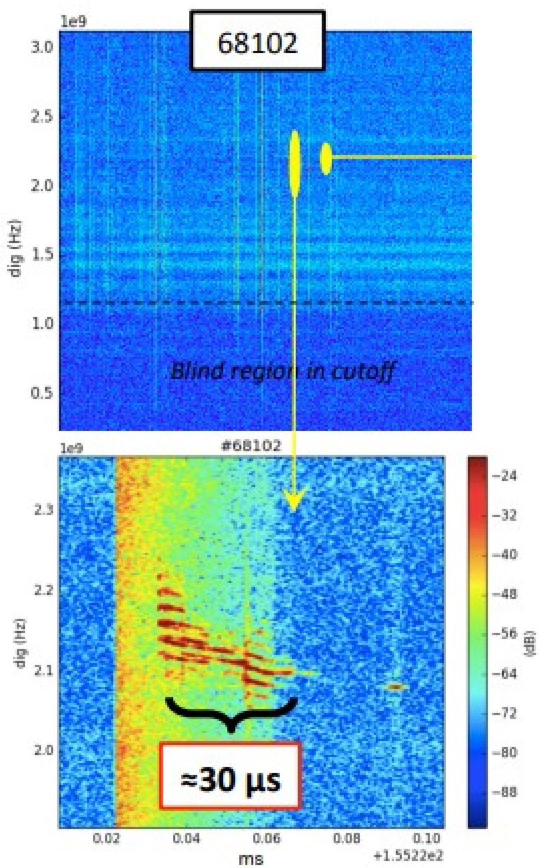


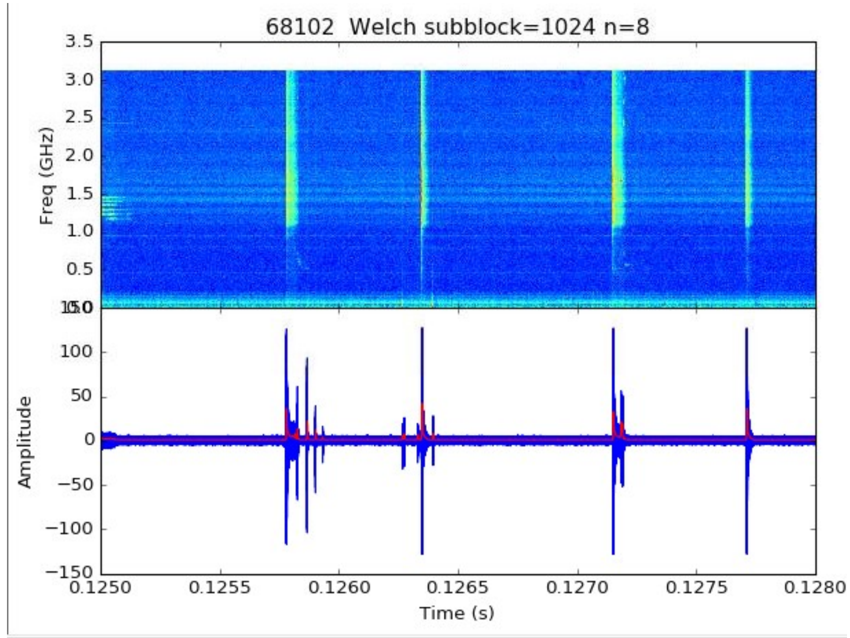
- RF spectrogram zoomed 0.5 - 1.2 GHz
- Raw signal normalized to saturation voltage
- Suprathermal ECE at 370 GHz, showing jumps at broadband bursts

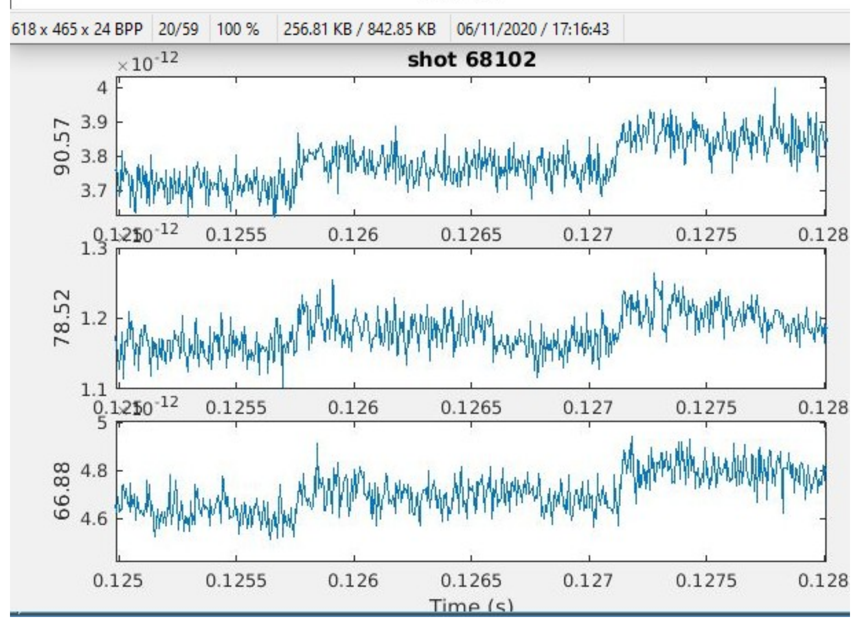
Besides impulsive anomalous Doppler instabilities, there are saturated ones producing coherent RF lines

TCV results with ex-vessel antenna (2020)

- Bursts and ECE jumps like in FTU
- Port cutoff at 1 GHz
- Coherent waves after bursts

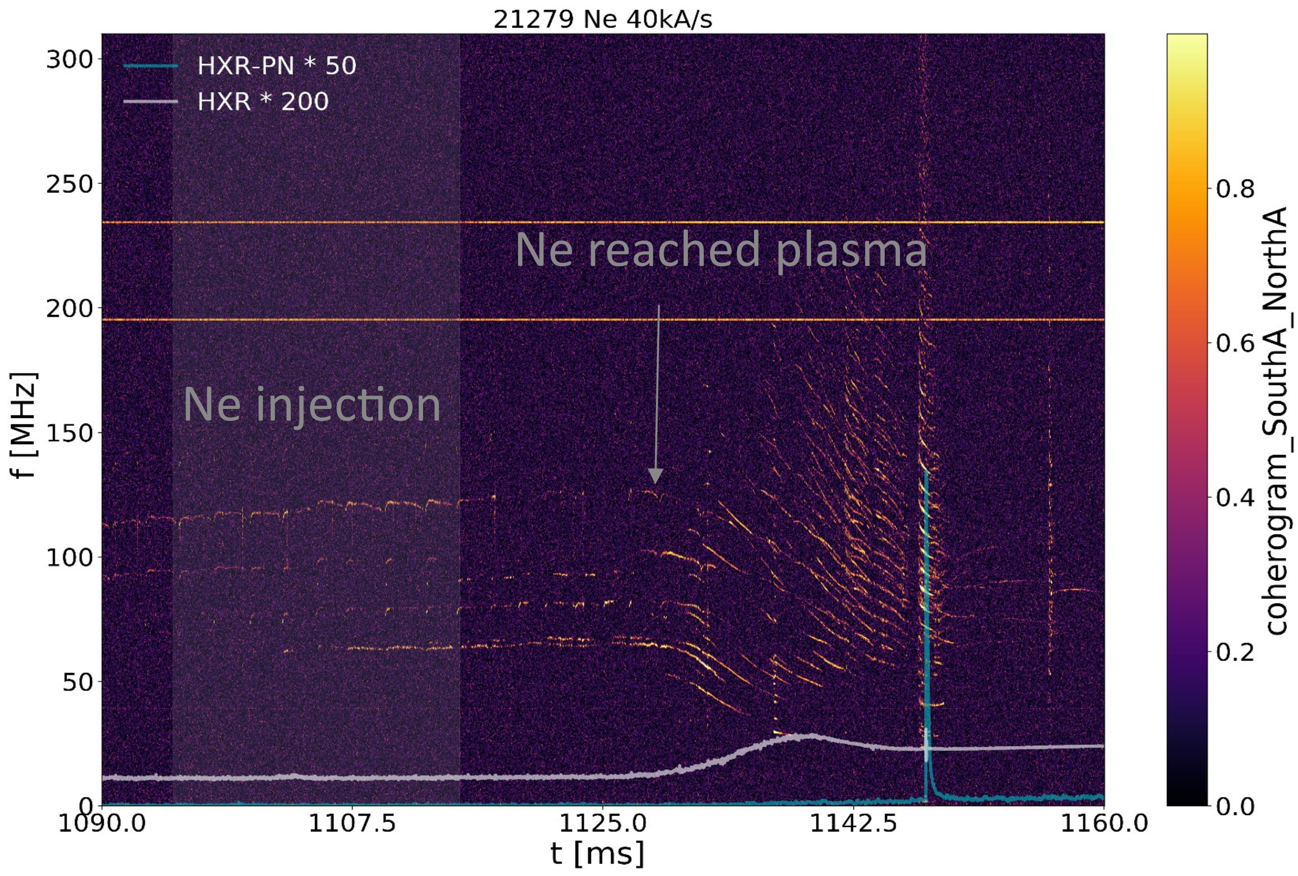






COMPASS 2020

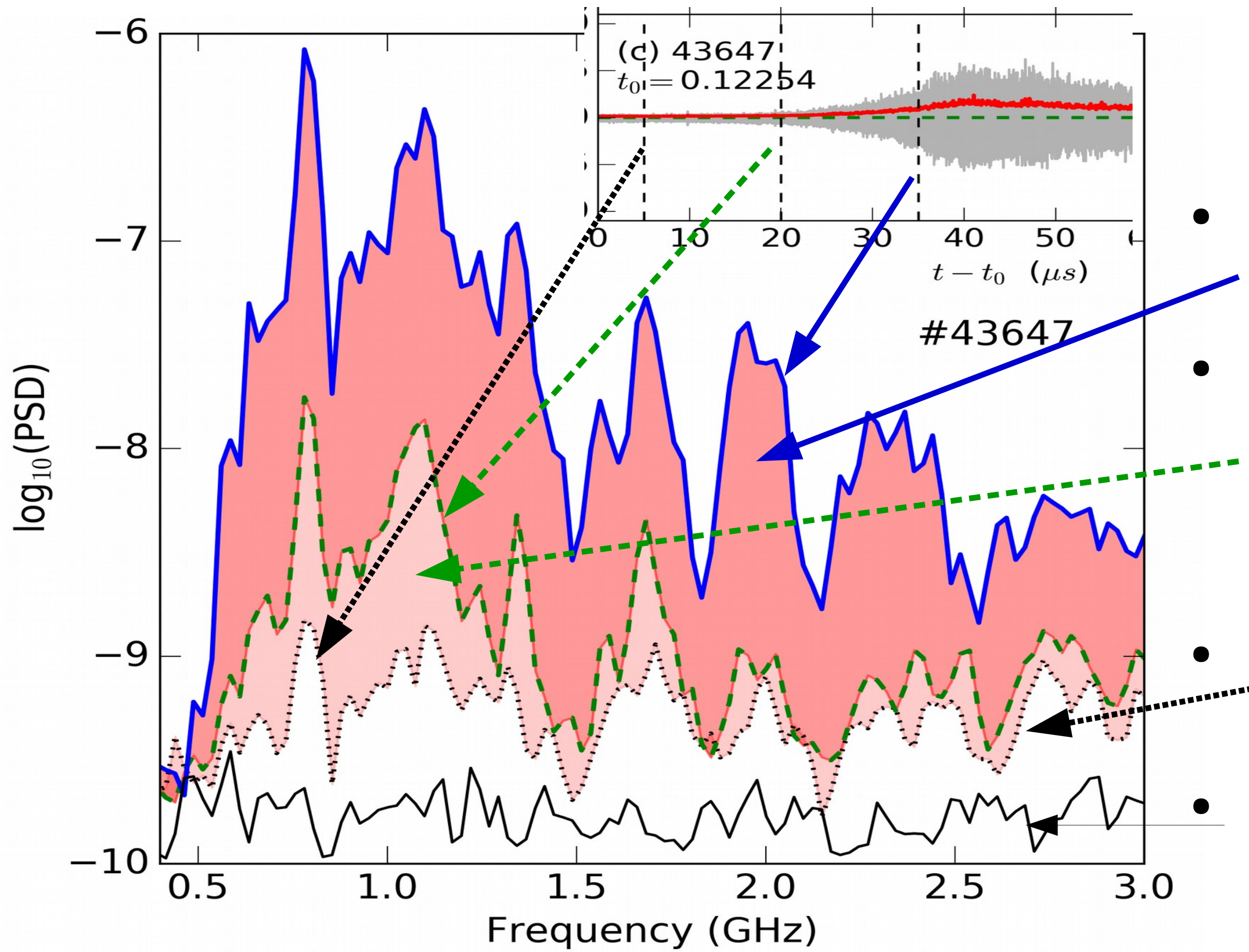
- Two in-vessel antennas
- Interesting dynamics in the 100 MHz range
- Other diagnostics can only detect the final burst



Conclusions

- Radio emission provides a sensitive diagnostic for kinetic instabilities affecting RE beams.
- Analysis of RE collective interactions provides inputs to:
  - improve predictive RE tools
  - optimize RE mitigation strategies.

Spectral analysis 2



- Broadening near saturation (solid)
- Enhancement at 0.6–1.7 GHz during early exponential growth (dashed)
- Baseline before the burst (dotted)
- Noise floor in the absence of RE

- Spectrum dynamics can provide input to modellers
- Local spectral features due to transfer function should be calibrated

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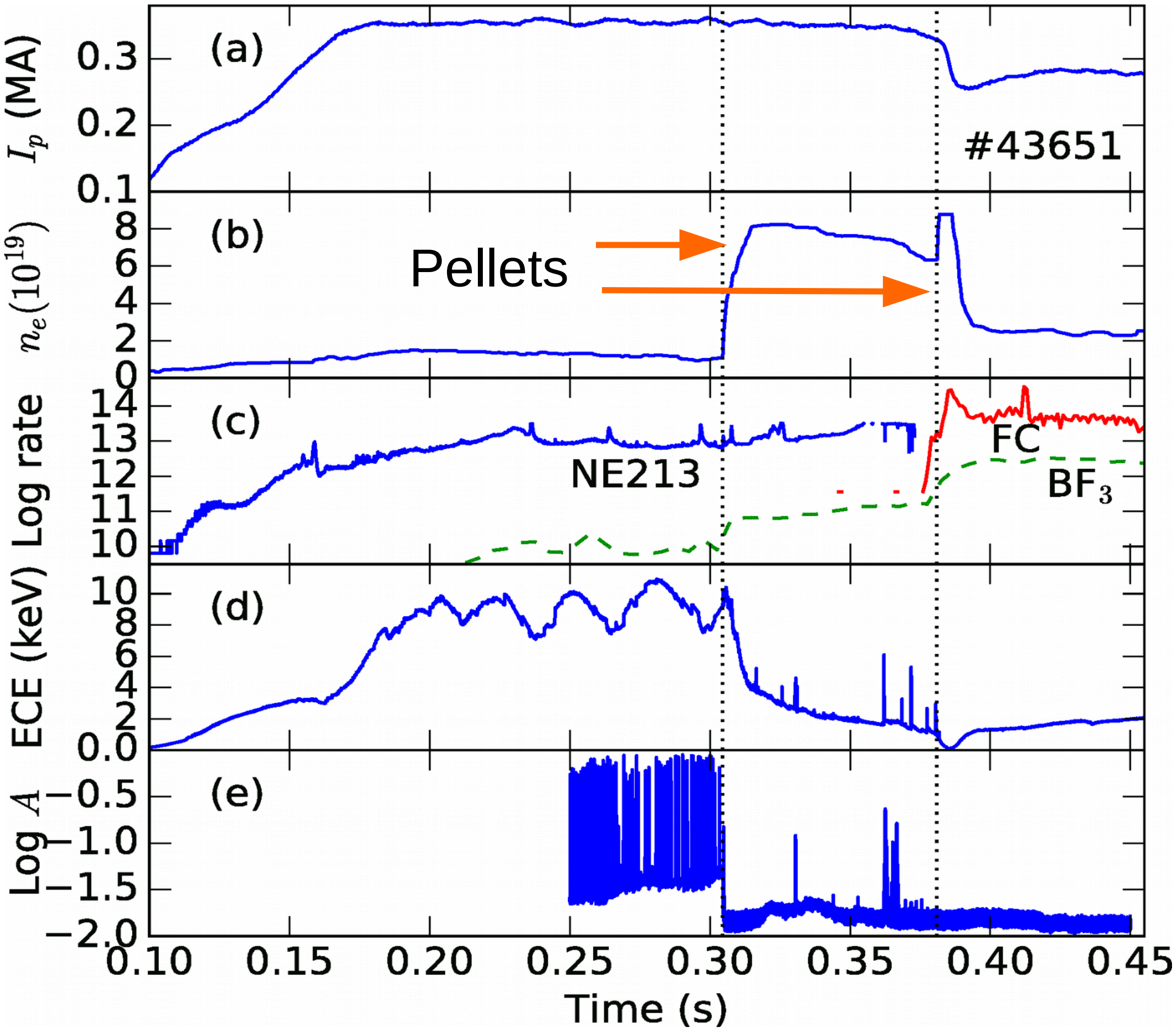
Response to plasma collisionality



- Plasma current
- Line average density
- Hard-x & photoneutrons
- ECE
- Radio emission in log scale

RE survive pellets, while RF bursts are quenched, likely by collisional wave damping