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Runaway electron driven high frequency kinetic instabilities during quiescent phase of KSTAR discharges

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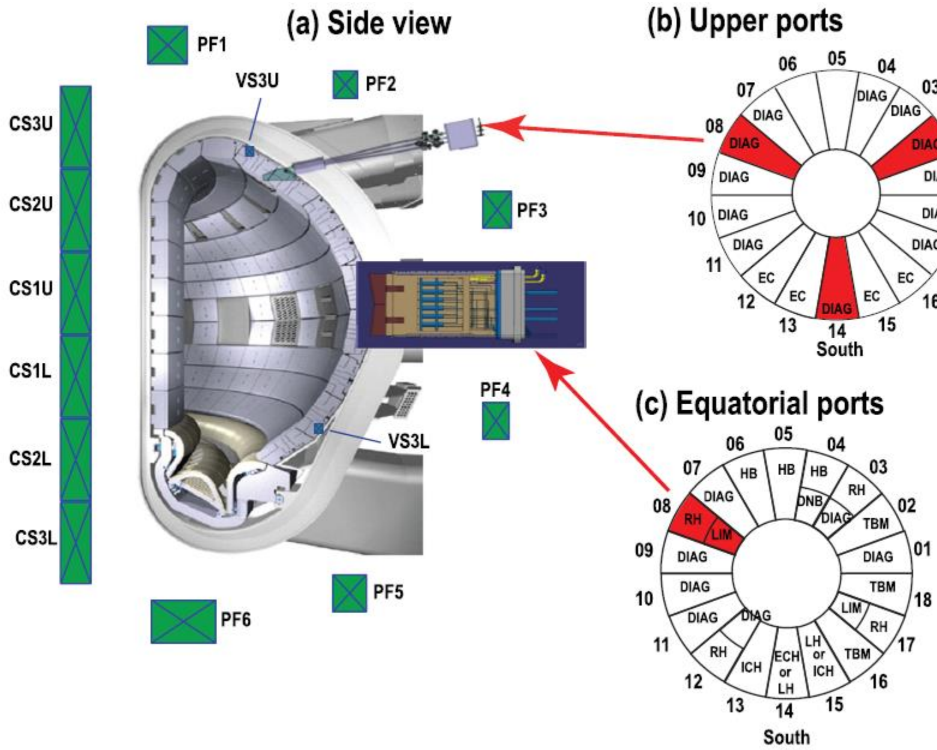
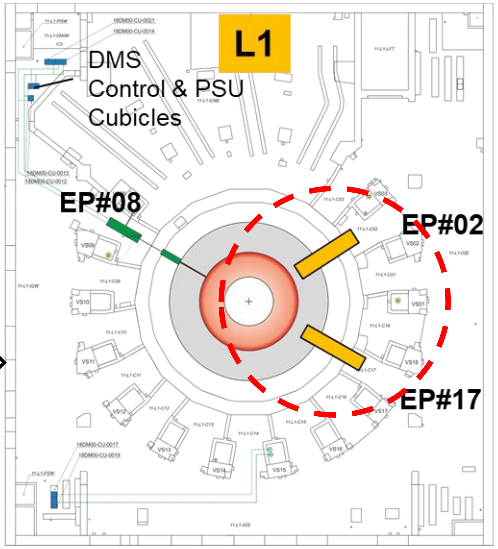
Motivation of this work

- ITER decided to install multiple shattered pellet injectors for high density during disruption.[1]
- The requirement mainly comes from the suppression condition of runaway electrons (REs).
- However, the level of requirement is still challenging when considering the disruption situation.
  - Abrupt cooling of plasma due to massive material injection



Upper SPIs (3 barrels/SPI) + equatorial SPIs (4 barrels/SPI)
= total 25 barrels

Added two SPIs
in addition to EP#08



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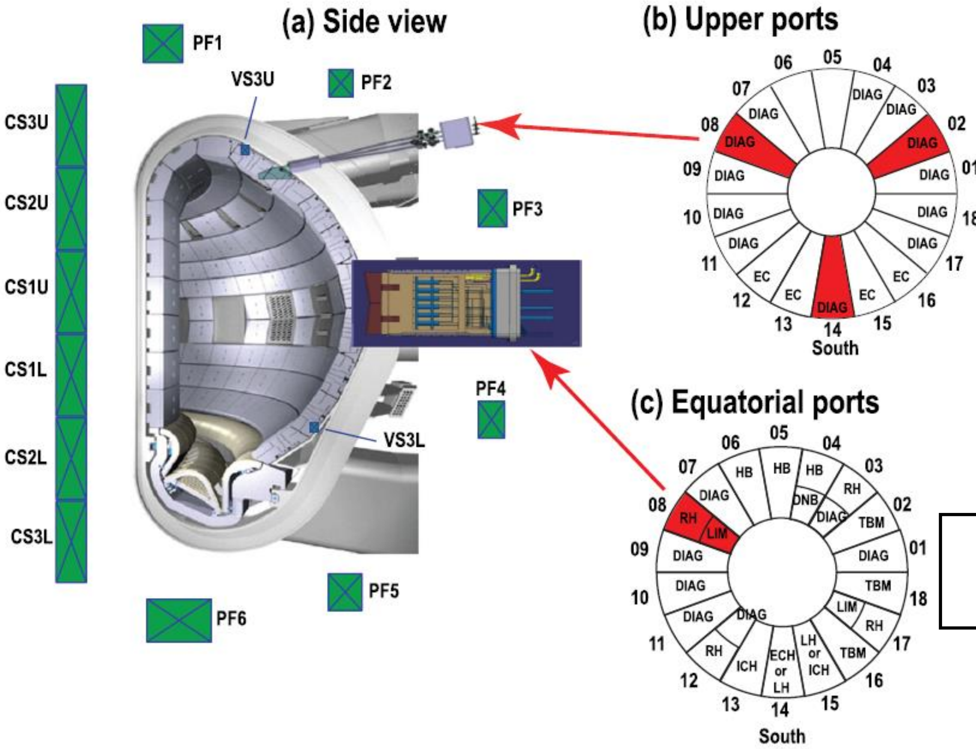
[1] M. Lehnen et al., IAEA fusion energy conference (2018).

Can we utilize instabilities (self-driven or externally driven) in mitigating the disruption?

- Like ELM mitigation/suppression by resonant magnetic perturbation[1]



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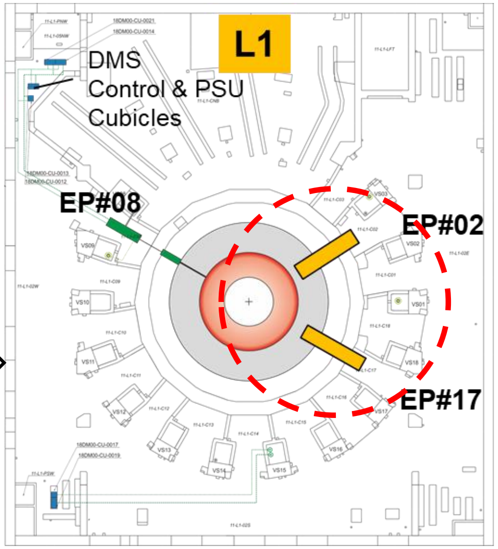

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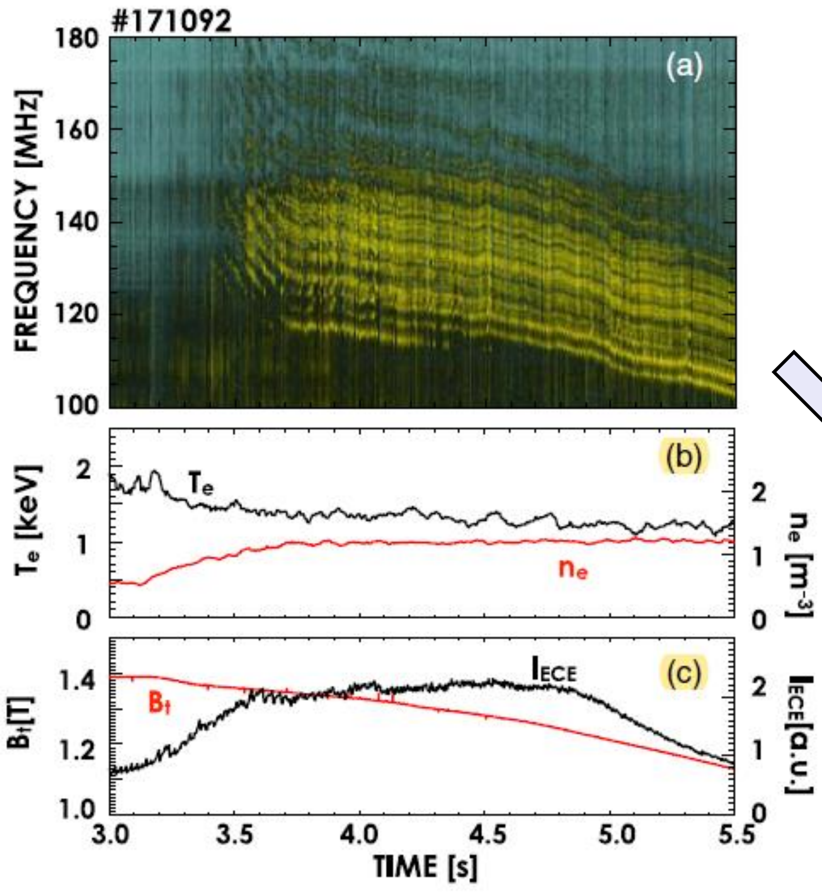
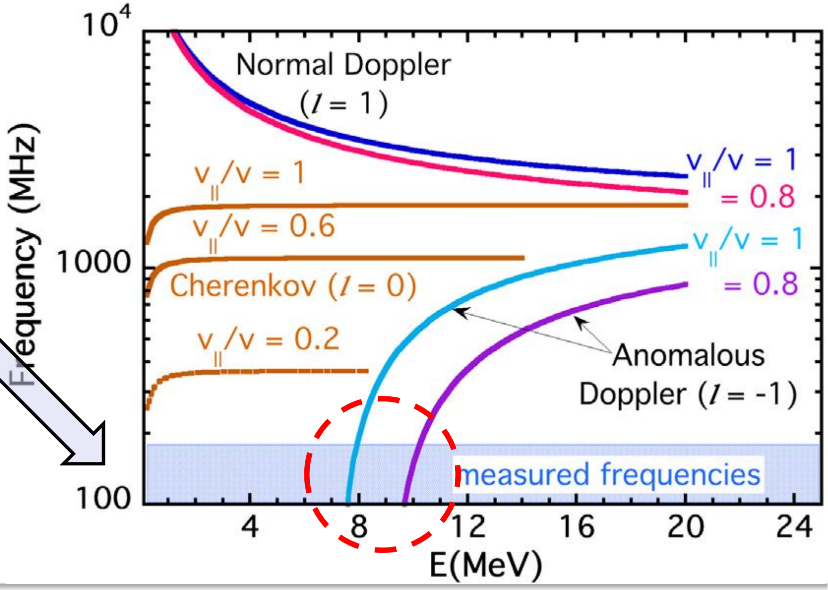
[1] J. Lee et al., Phys. Rev. Letters (2016).

Previous measurement of runaway electron (RE) driven kinetic instabilities (KIs) in DIII-D

- Due to the limitation of measurements, DIII-D measured relatively low frequency KIs.[1]
- It corresponds to anomalous Doppler resonance of REs (~10^2 MHz order).
- It is expected that
  higher frequency KIs (~GHz order) also exist and provide the bulk dissipation of REs.[2,3]

[1] D.A. Spong et al., Phys. Rev. Letters (2018).
[2] C. Liu et al., Phys. Rev. Letters (2018).
[3] C. Paz-Soldan et al., Nucl. Fusion (2019).

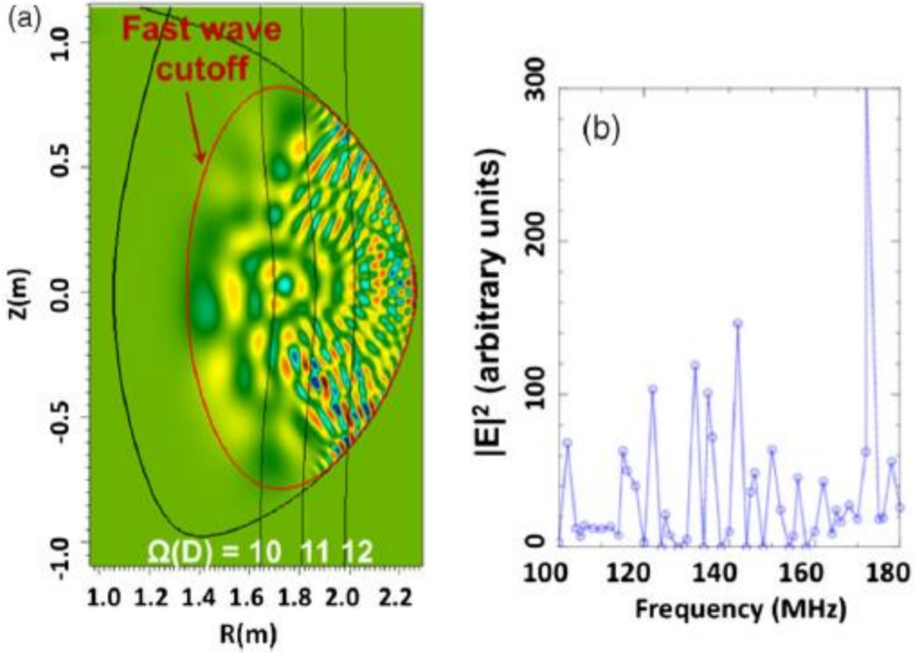




Mode characteristics of ~10^2 MHz order KIs and higher ones

- Measured low frequency KIs (~10^2 MHz order) have harmonic band structures.
- It can be explained either by[1]
    - Eigenmodes related to bounded and periodic nature of tokamak
    - Wave cut-off
    - Damping effect
    - Scattering off of other plasma waves.

- It is expected that ~GHz order KIs are evanescent[2].
- So it is hard to measure ~GHz order KIs in fusion plasma with ex-plasma diagnostics.
- How can we detect/measure them?



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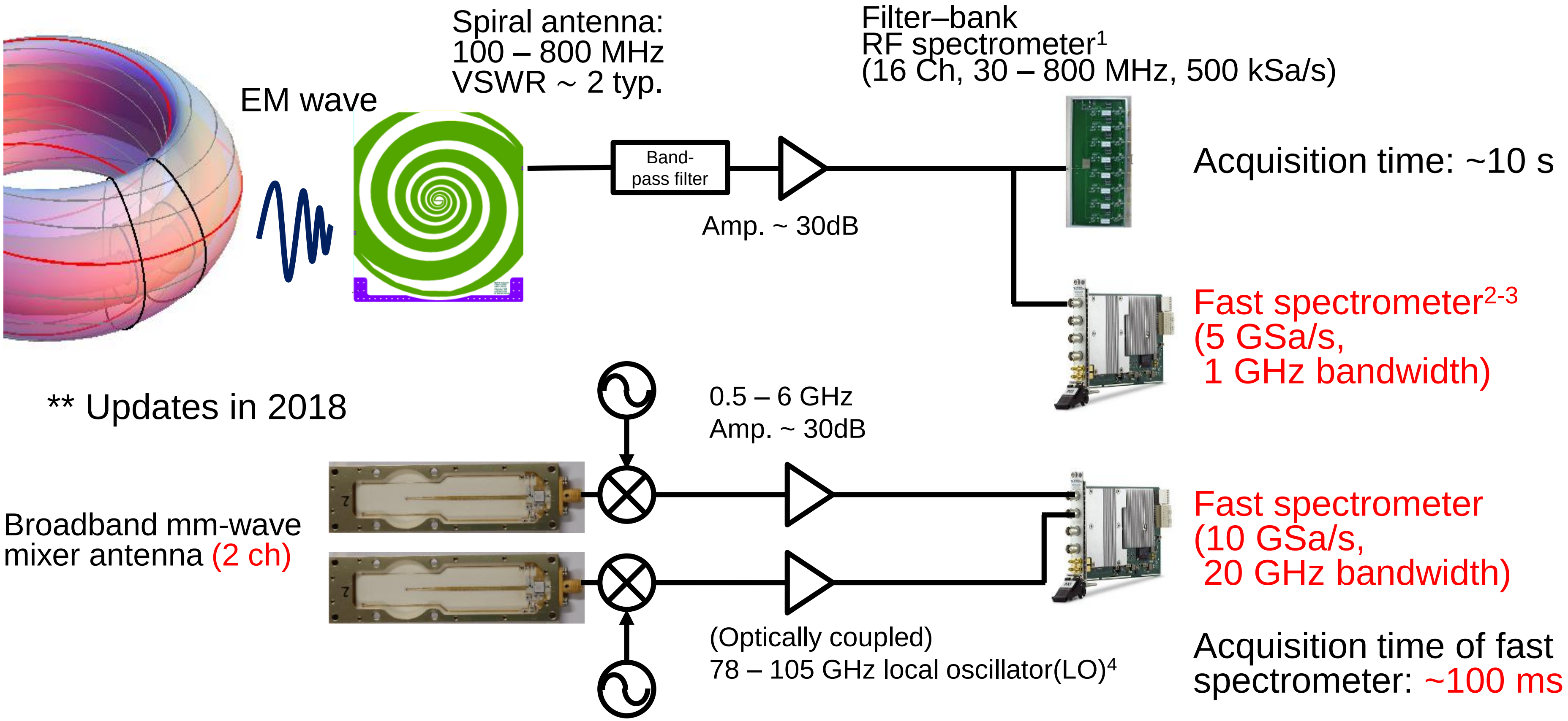
[1] D.A. Spong et al., Phys. Rev. Letters (2018).

[2] P.B. Aleynikov et al., Nucl. Fusion (2015).

If KIs affect on RE pitch, it should be carried on electron cyclotron emission.

Courtesy of G. Yun et al.



EM wave

Spiral antenna:
100 – 800 MHz
VSWR ~ 2 typ.

Band-pass filter

Amp. ~ 30dB

Filter–bank
RF spectrometer[1]
(16 Ch, 30 – 800 MHz, 500 kSa/s)

Acquisition time: ~10 s

Fast spectrometer[2-3]
(5 GSa/s,
1 GHz bandwidth)

** Updates in 2018

0.5 – 6 GHz
Amp. ~ 30dB

Broadband mm-wave
mixer antenna (2 ch)

Fast spectrometer
(10 GSa/s,
20 GHz bandwidth)

(Optically coupled)
78 – 105 GHz local oscillator(LO)[4]

Acquisition time of fast
spectrometer: ~100 ms

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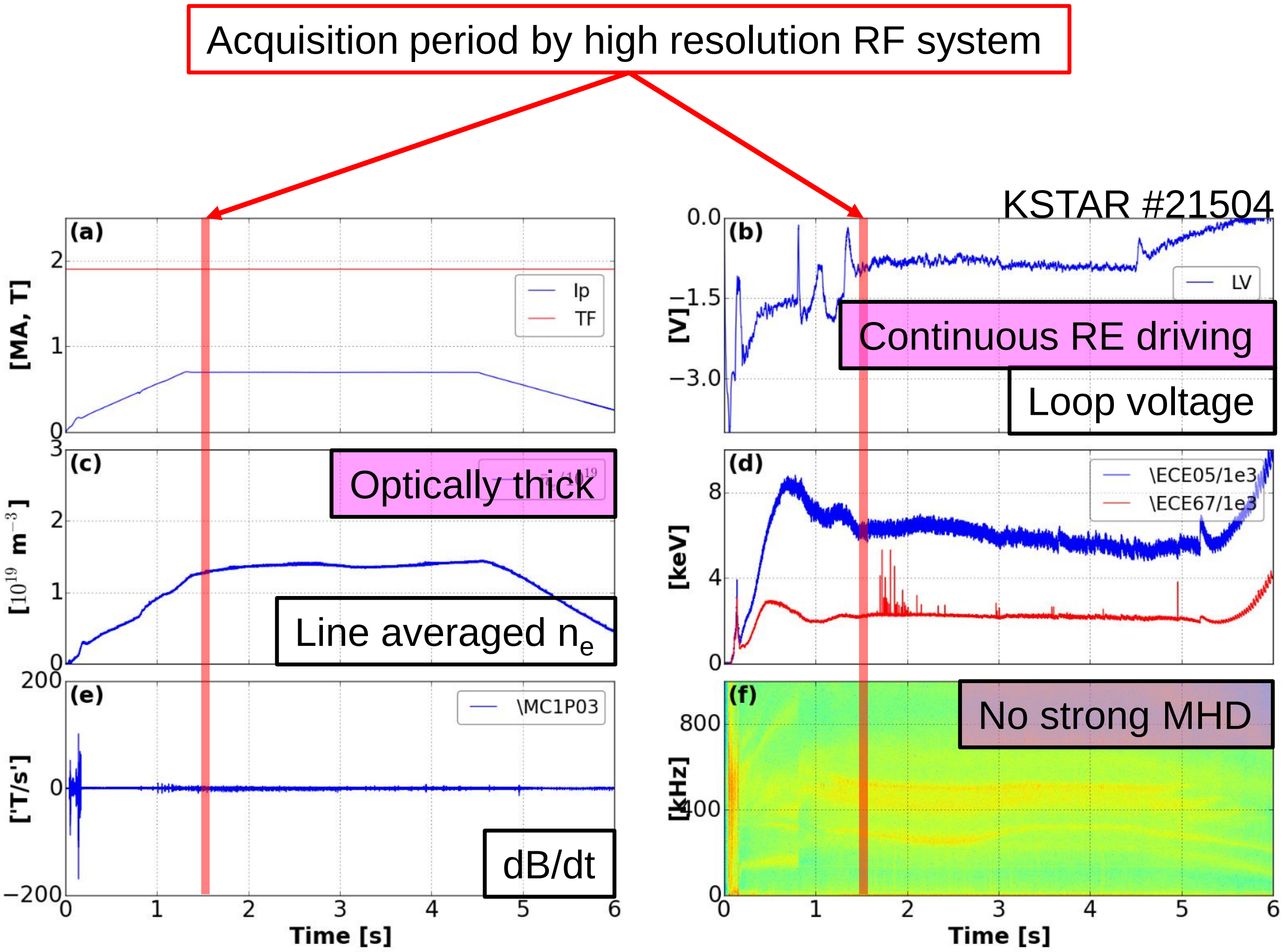
[1] J. Leem et al., JNIST (2012).
[2] S.G. Thatipamula et al., PPCF (2016).
[3] M.H. Kim et al., Nucl. Fusion (2018).
[4] Y.B. Nam et al., Rev. Sci. Inst. (2018).

Pure Ohmic discharge with relatively low density and high loop voltage continuously drives REs.



Acquisition period by high resolution RF system

Continuous RE driving

Loop voltage

Optically thick

Line averaged n_e

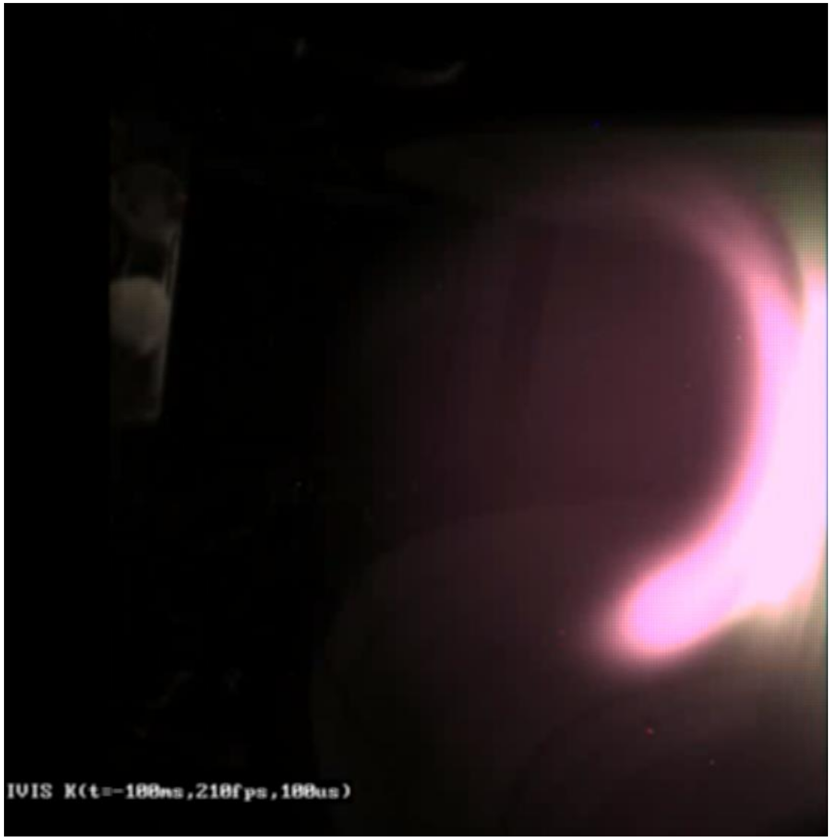
dB/dt

No strong MHD

Analysis of synchrotron radiation pattern (progressing)

- Synchrotron radiation in visible camera supports the existence of high energy REs (>10 MeV).

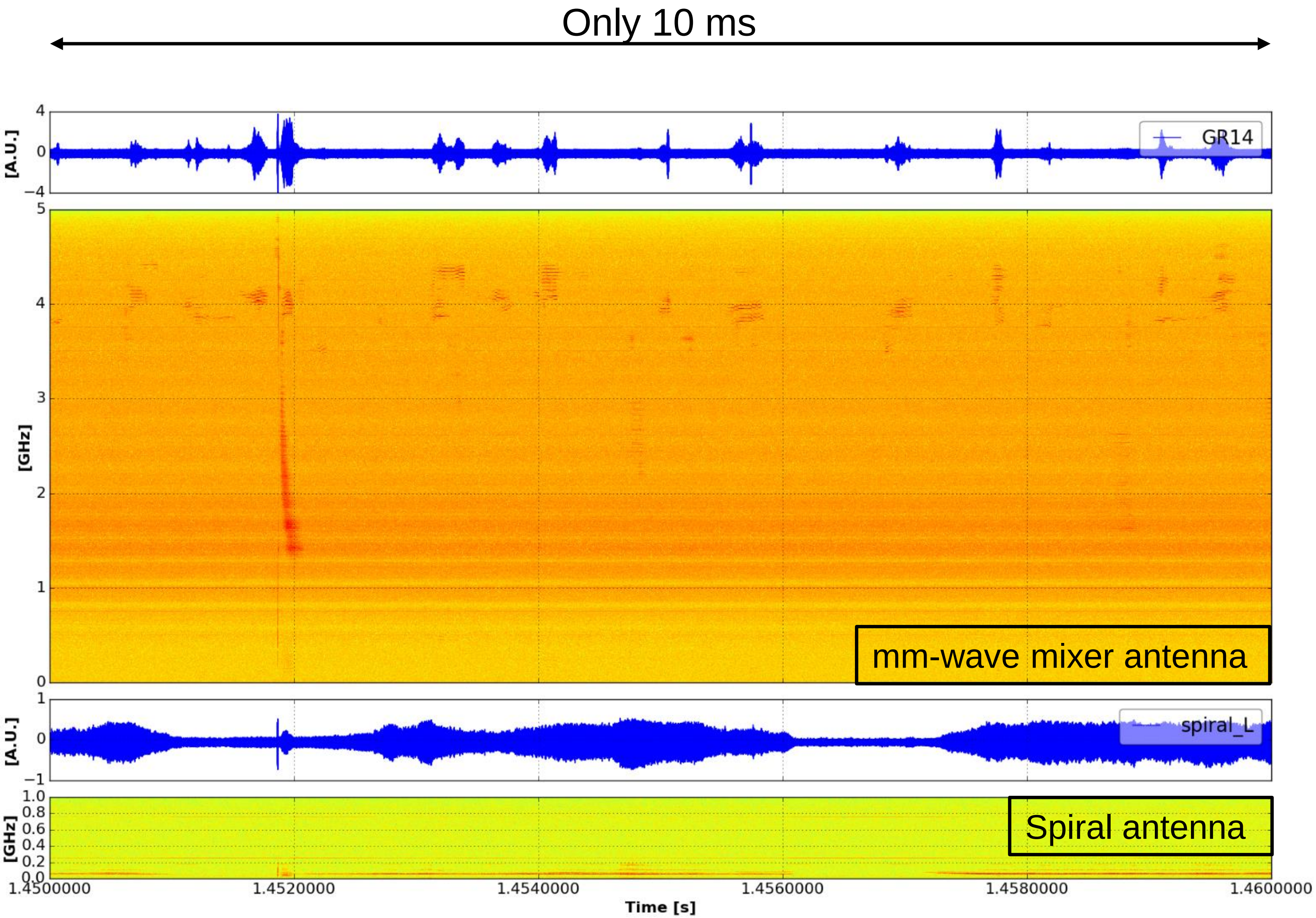
- RE energy range and pitch could be deduced from IR image.
  - Analysis is progressing with IR image.



Visible camera at
t=1.485 sec of #21504

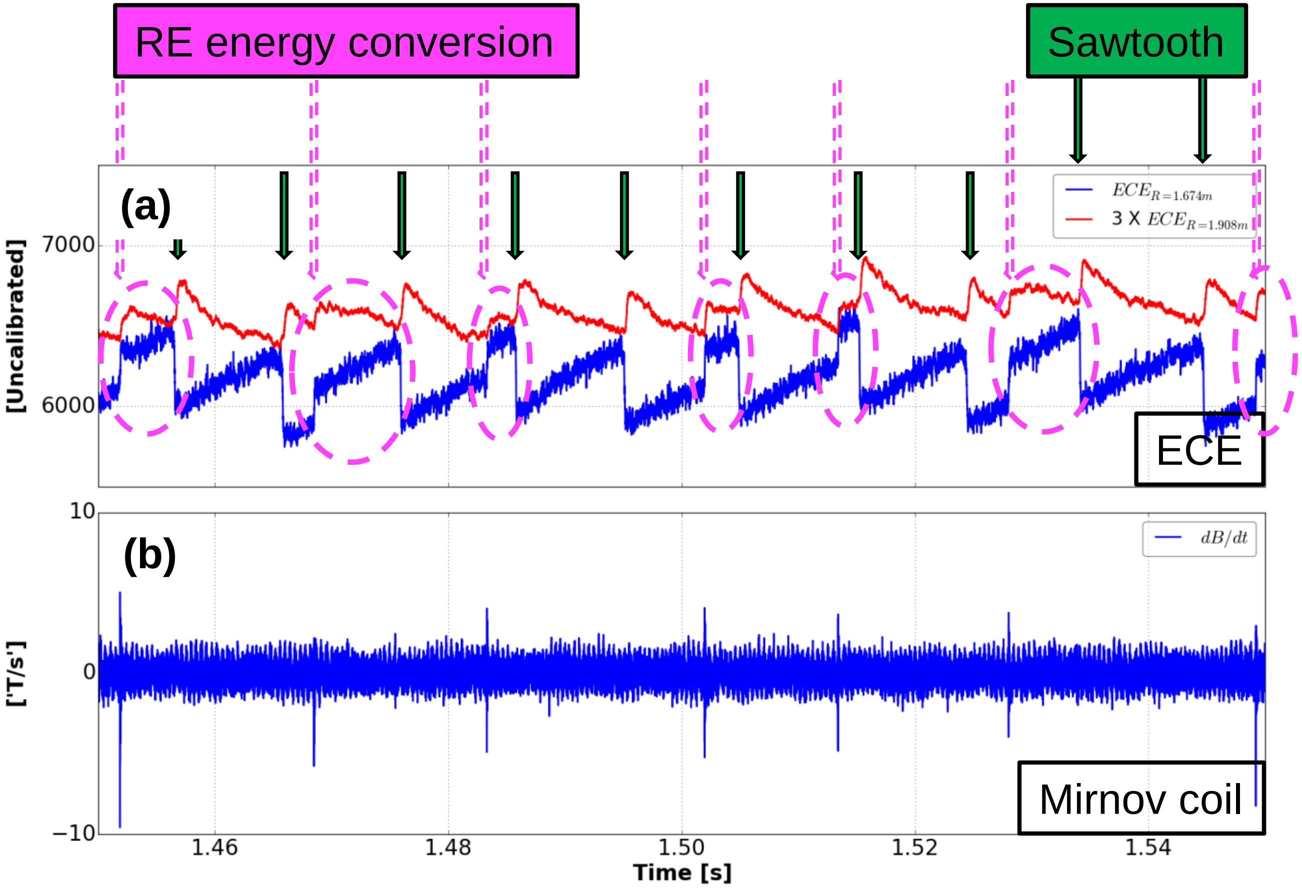
High resolution RF diagnostic system in KSTAR opened *new zoology* of RE driven kinetic instabilities.

Only 10 ms

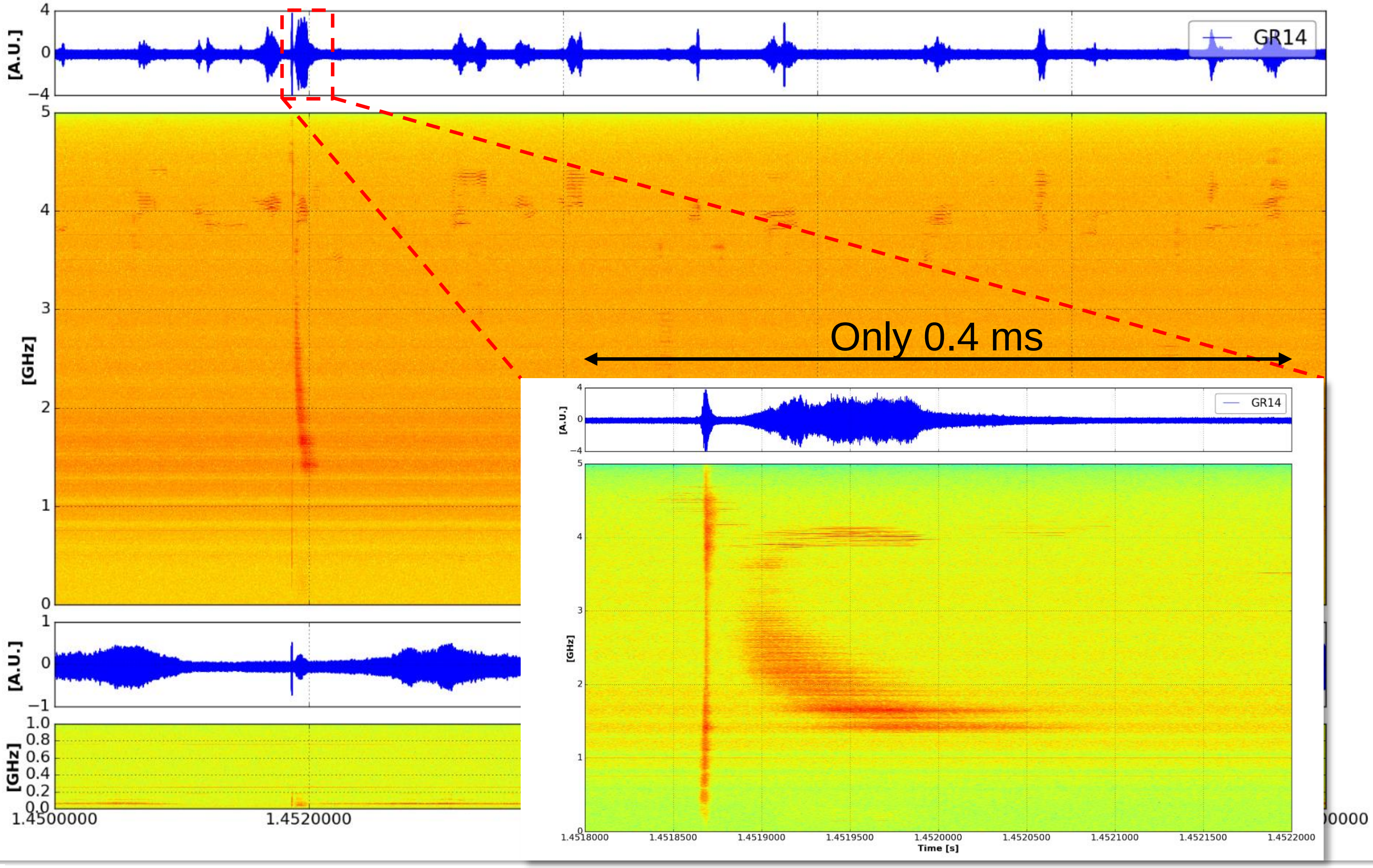


Strong RE energy conversion from parallel to perpendicular energies were observed in timings of certain specific kinetic instabilities.

- Unlike sawteeth, T_e is abruptly raised in both sides of inversion radius.
- Mirnov coils only respond significantly at the timing of RE energy conversion.



The specific kinetic instability consists of two parts: strong short burst and following wide spectrum

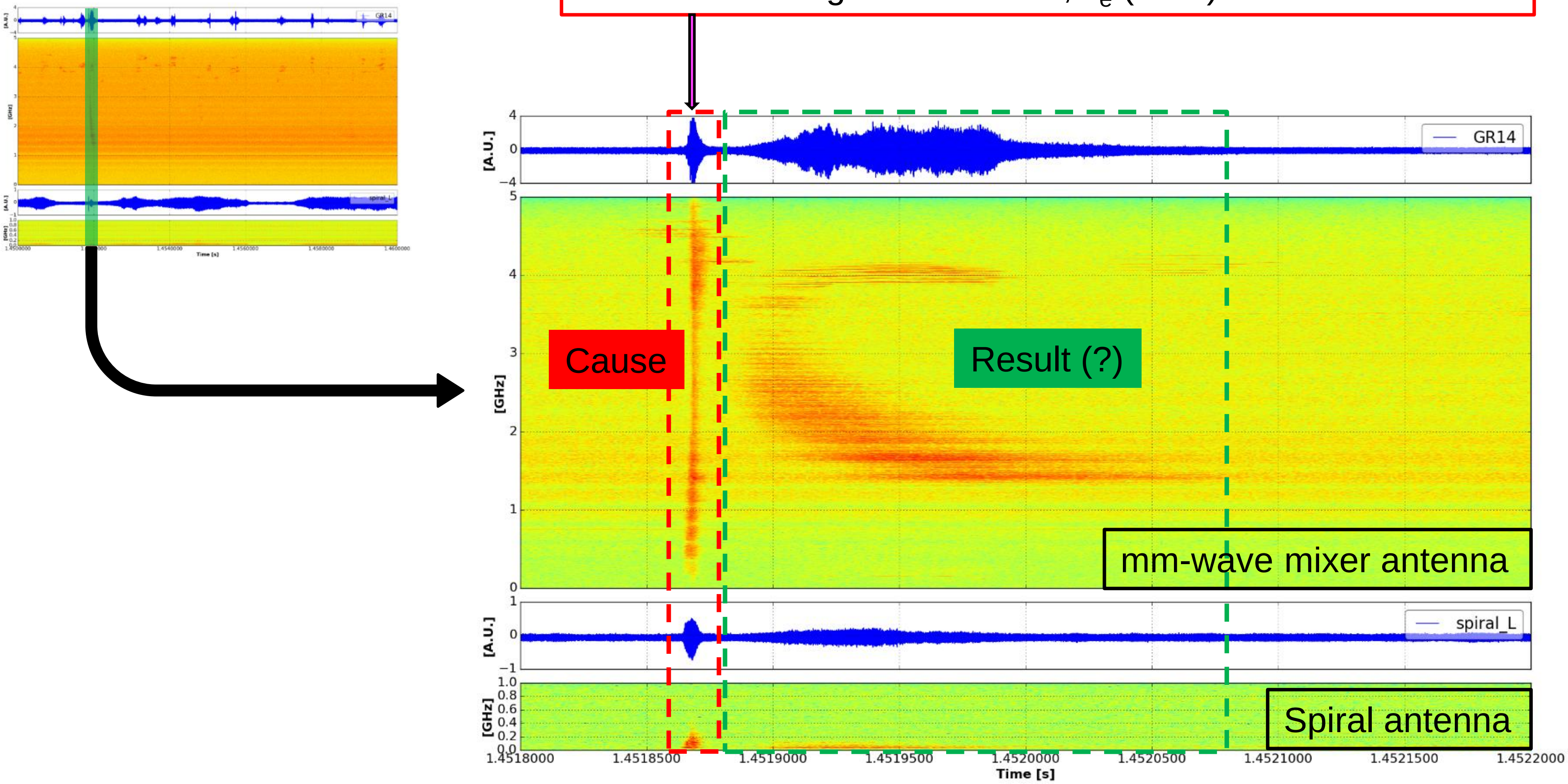


Only 0.4 ms

Only short burst (~10 μs) instability caused significant RE energy conversion.

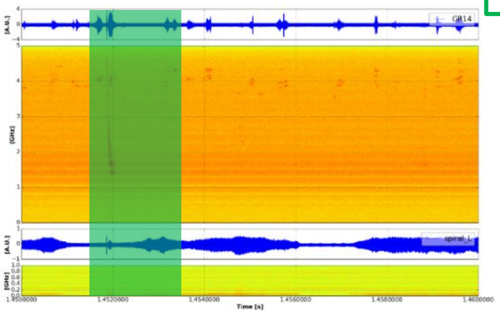
- Spiral antenna (direct EM field measurement of wave) also significantly responds to the burst.
  - ECE and spiral signals do not necessarily respond together.

Just at the timing of short burst, T_e (ECE) starts to be raised.

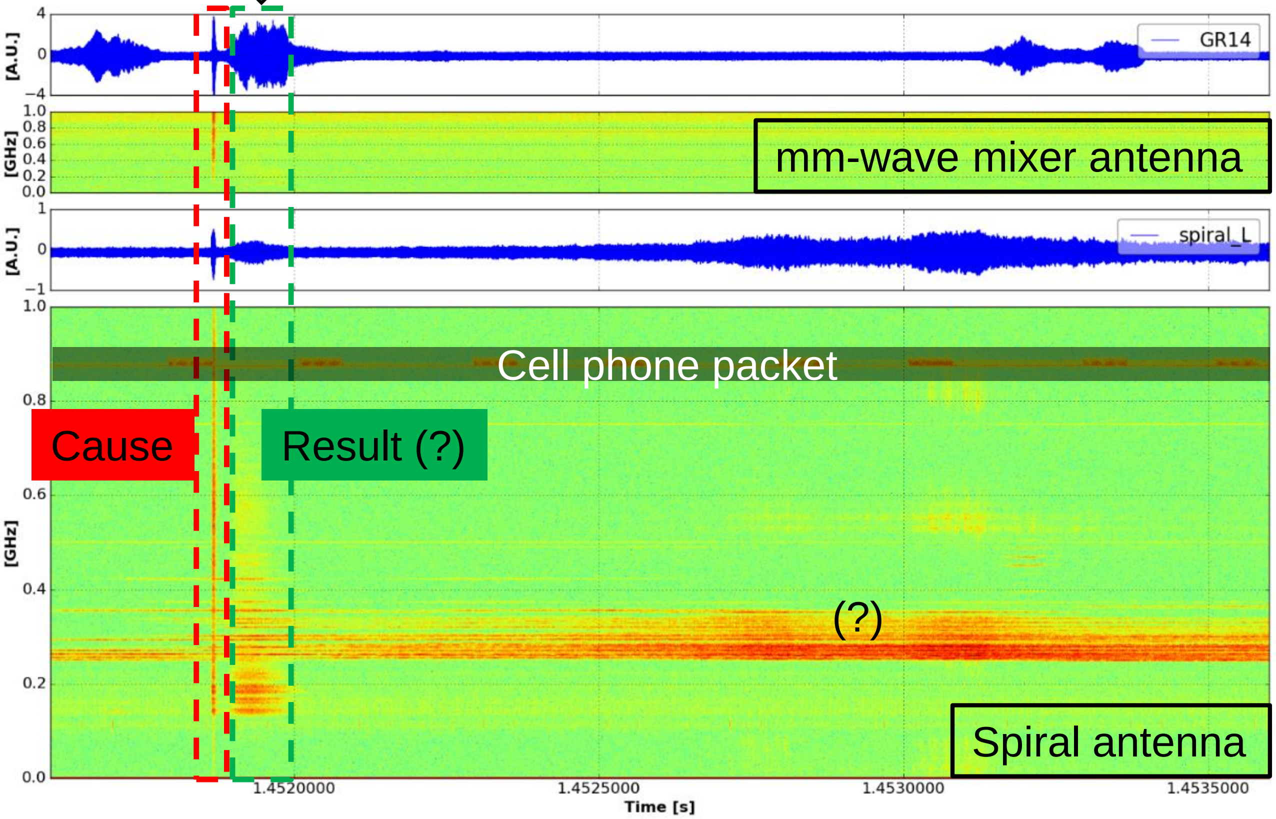


RF signal measured by external spiral antenna exhibited harmonic band structure.

- The band gaps correspond to deuterium ion cyclotron frequency (Δf ~ 10 MHz).
- 100~400 MHz bands show strong activity.



Just after the burst, more harmonics appears in addition to existing ones.



mm-wave mixer antenna

Cell phone packet

Cause

Result (?)

(?)

Spiral antenna

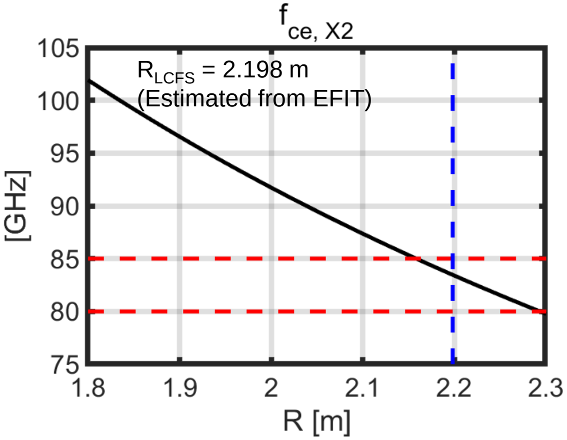
This resembles the signature during ELM crashes in H-modes although the causes of burst are *totally* different each other.

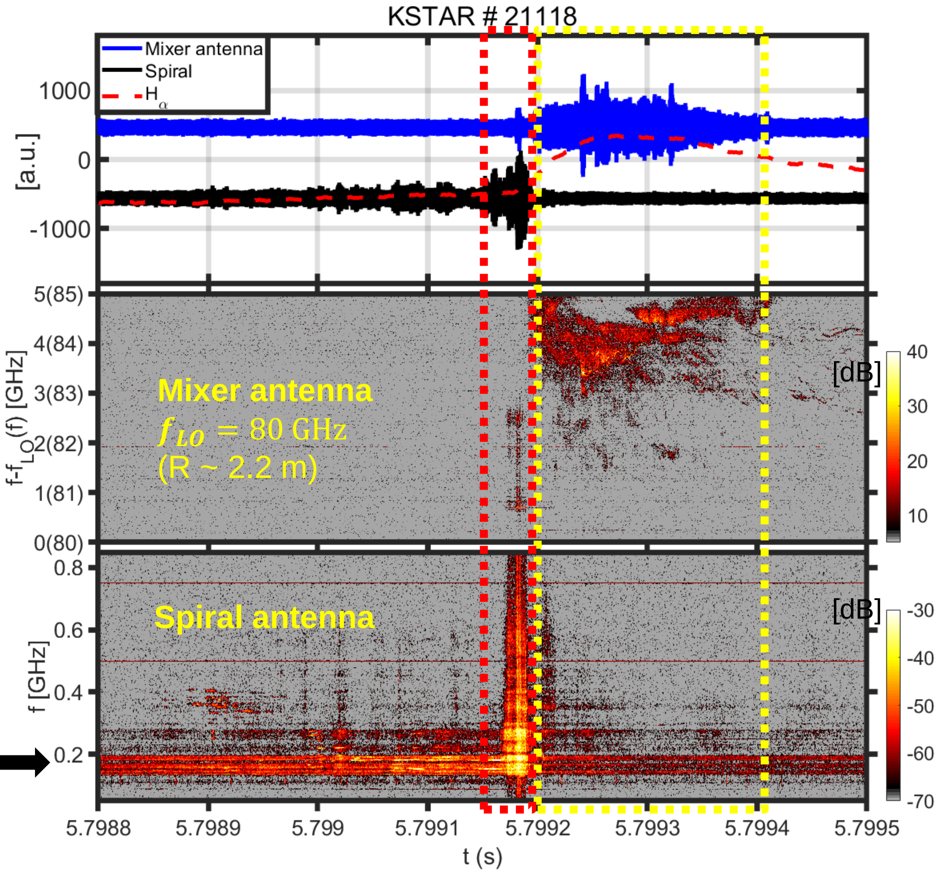
Courtesy of M.H. Kim et al.

KSTAR #21118

$B_0 = 1.82$ T, $I_p = 500$ kA,

$q_{95} \sim 6$, $\langle n_e \rangle = 3 \times 10^{19}\ \mathrm{m}^{-3}$





High harmonic deuterium ion cyclotron emission (0.14 – 0.4 GHz) at the edge region[1-2]

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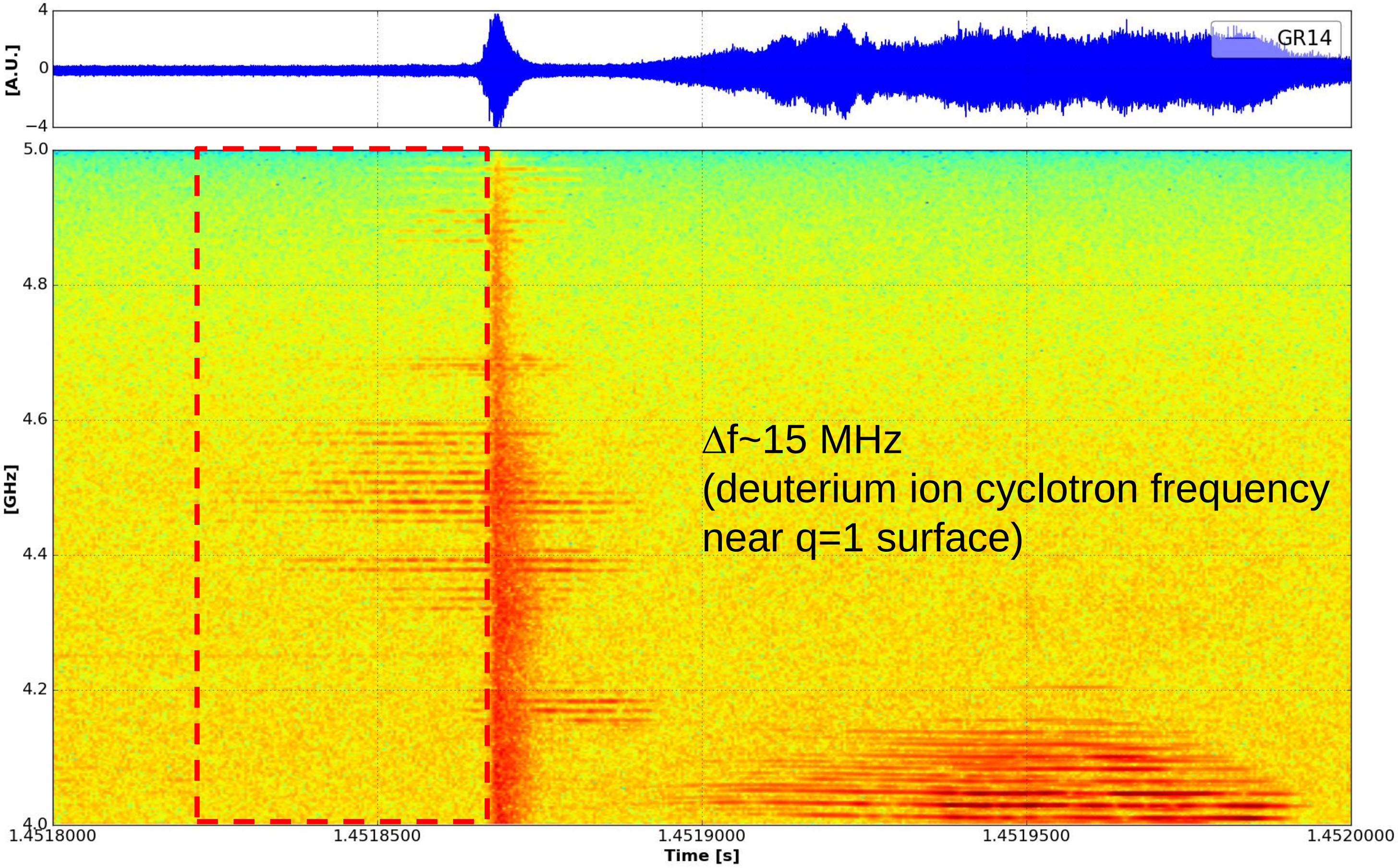
[1] S.G. Thatipamula et al., PPCF (2016).

[2] M.H. Kim et al., Nucl. Fusion (2018).

If so, what causes the short RE burst?

- ELM burst: P-B instability → ELM crash → relaxation process
- RE burst: pre-cursor of instability (?) → RE burst → relaxation process

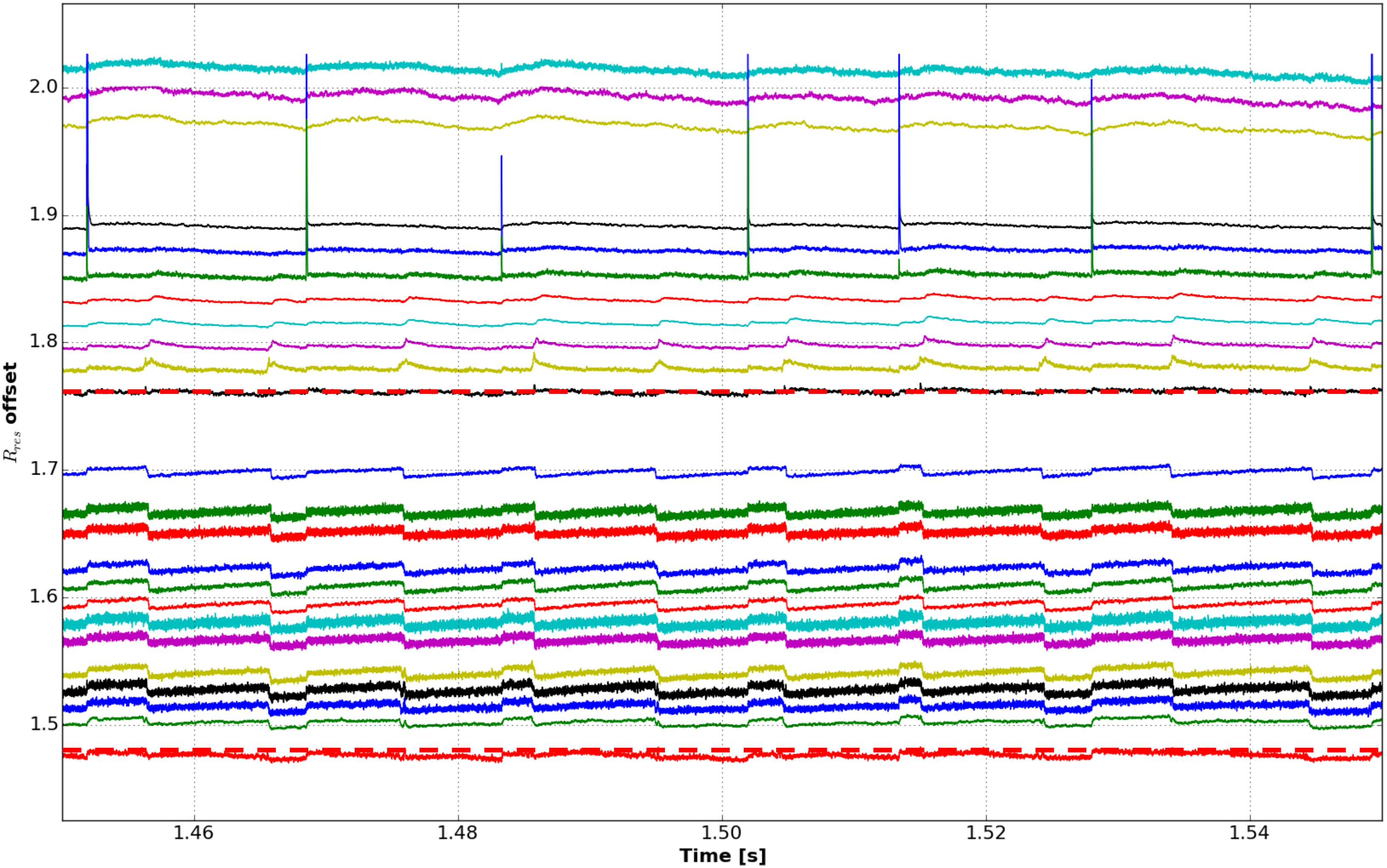
- In most cases (not always), the below precursor appears before the RE burst.
  - Why not always? Do we still see the tip of the iceberg?



Δf~15 MHz
(deuterium ion cyclotron frequency
near q=1 surface)

The short burst is localized in specific radius.

- Specific channels of ECE radiometer exhibit very strong spikes in addition to long sustaining jump-up of Te.

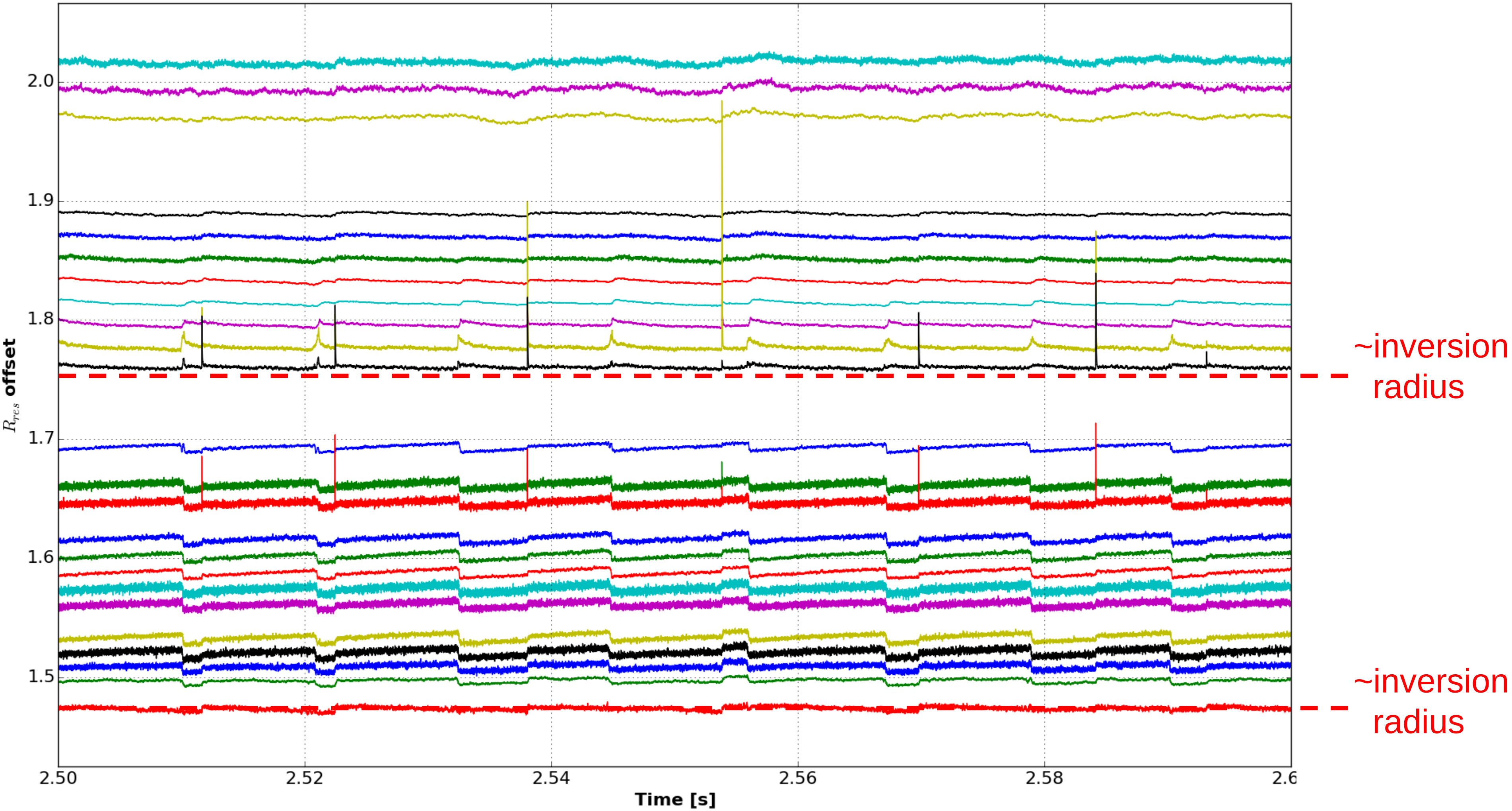


~inversion radius

~inversion radius

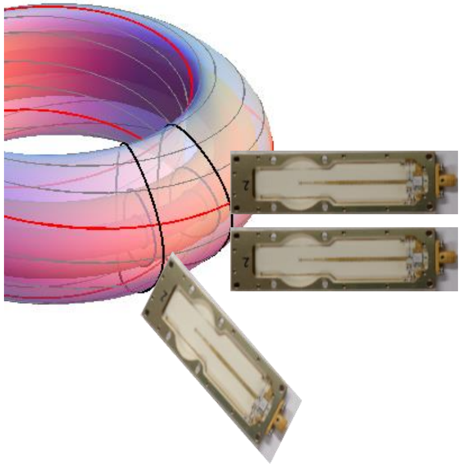
The short burst is localized in specific radius.

- Sometimes, the spikes emerge simultaneously in distant channels.



Near future works

- So far, we have focused on the quiescent phase of discharges.
  - Relatively low electron density (~1x10^{19} m^{-3}) and high electron temperature (~keV)
  - With moderately high electric field
- More interesting phase is a disruptive phase w/ or w/o massive material injection (SPI or MGI).
  - Very high electron density (~10^{20} m^{-3}) and low electron temperature (~10 eV)
  - With very high electric field
- In upcoming campaign, we will try to measure RE driven KIs in disruptive phases.
- Further study in quiescent phase is still needed for revealing the characteristics of observed KIs.
  - Dispersion relation of waves:
    - Simultaneous measurement of k_{parr} and k_{perp}
  - Characteristics of KIs depending on discharge conditions:
    - Dependencies on density, toroidal field, and etc.
  - Role/characteristics of KIs without significant RE energy conversion
  - Role/characteristics of ~10^2 MHz KIs only measured in spiral antenna
- Measurement of RE energy distribution
  - Analysis of synchrotron radiation pattern: infra-red and visible images
  - Development of hard x-ray diagnostic system (?)



High resolution RF diagnostics at two different toroidal position

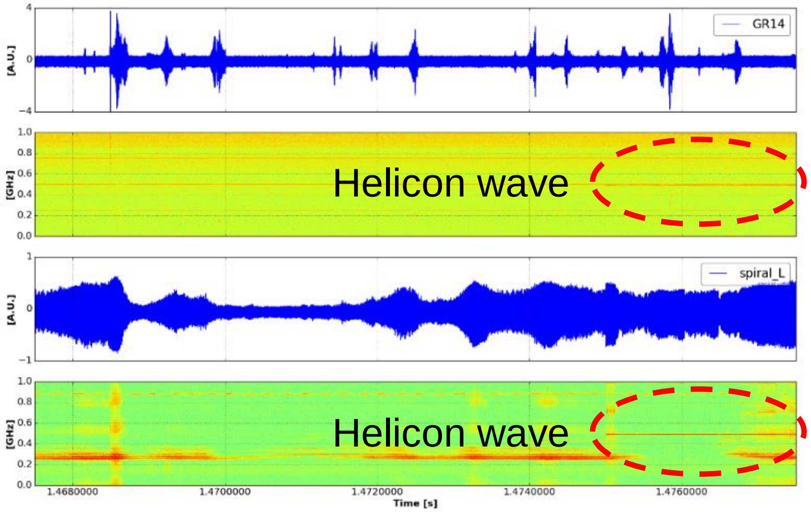
Far (?) future works: control of RE by externally driven modes

- In 2018 campaign, we *naively* injected whistler wave with using the prototype of helicon system.
  - Power~10 kW, frequency=475 MHz, $n_{//}$=3
  - It seems that the coupling to plasma was negligible likely due to multi-factoring.

- There is no meaningful effect on RE driven instabilities.
- However, we should pursue the control of REs by externally driven mode for reliable RE control.[1]
- We might need to optimize *integrated* disruption mitigation strategy possibly between
  - massive material injection (for thermal and EM loads) and
  - external mode driving (for REs).

- Collisional plasma during post-disruption phase could be unfavorable for external mode driving.

Mostly stray field
through outside of plasma (?)



Helicon wave

Helicon wave

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[1] Z. Guo et al., Phys. Plasmas (2018).
[2] H. Wi et al., KSTAR conference (2017).

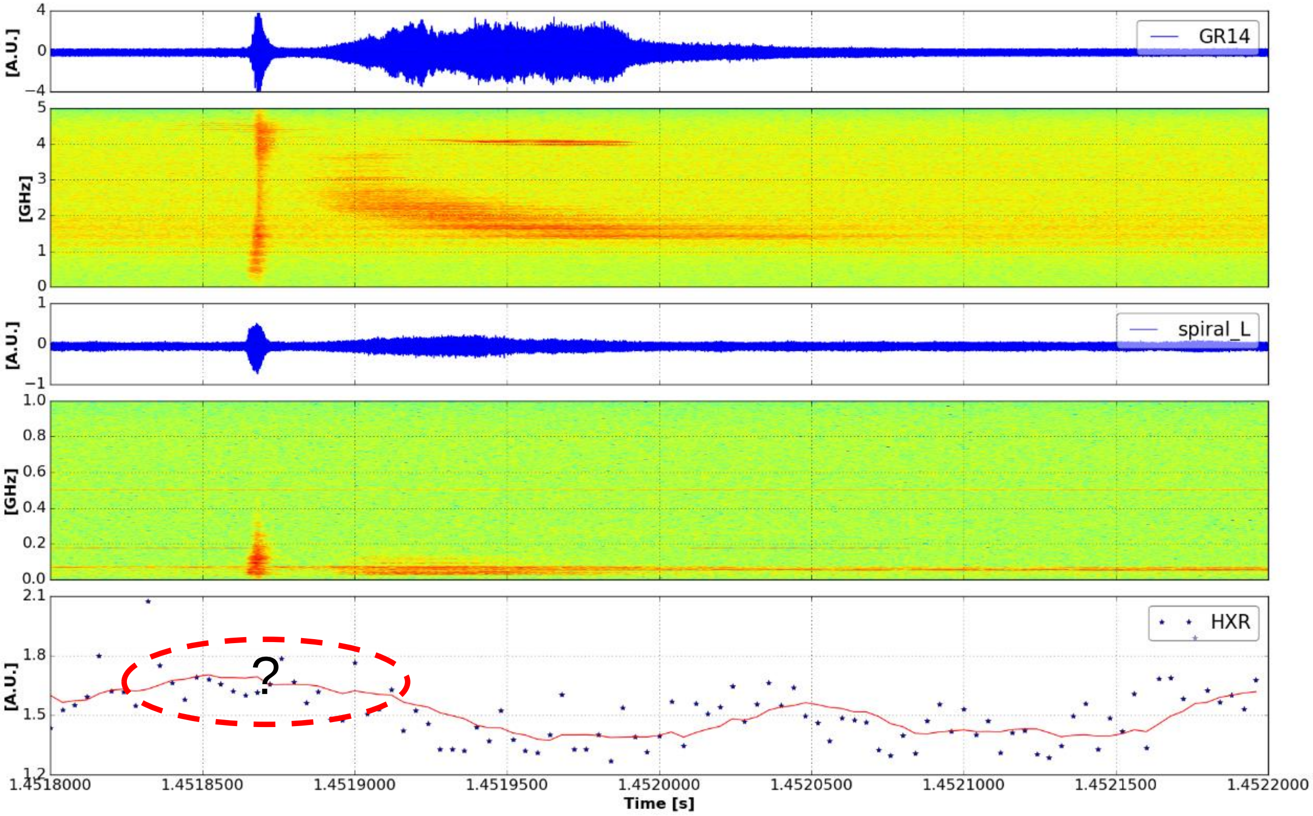
Back-ups

- Back-ups

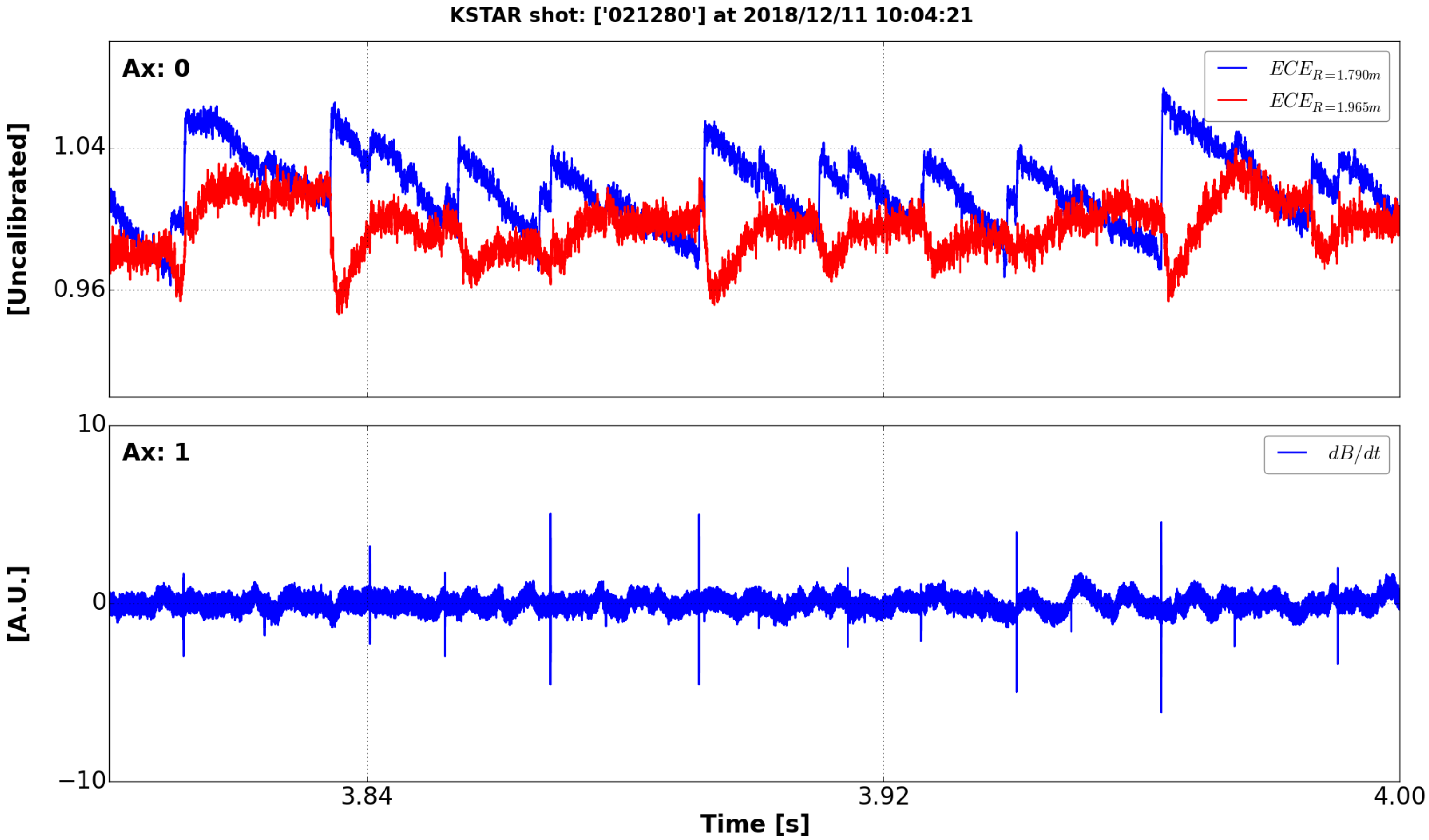
External hard x-ray detector[1] cannot catch meaningful signature at the RE energy conversion.

- Development of proper hard x-ray diagnostic system is essential for future study.
  - For example, gamma ray imager[2] in DIII-D

[1] J.M. Jo et al.
[2] D.C. Pace et al., Rev. Sci. Inst. (2016).



Universality of RE energy conversion in other KSTAR discharge



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