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Investigation of the nonlinear interaction of fast ion driven plasma waves

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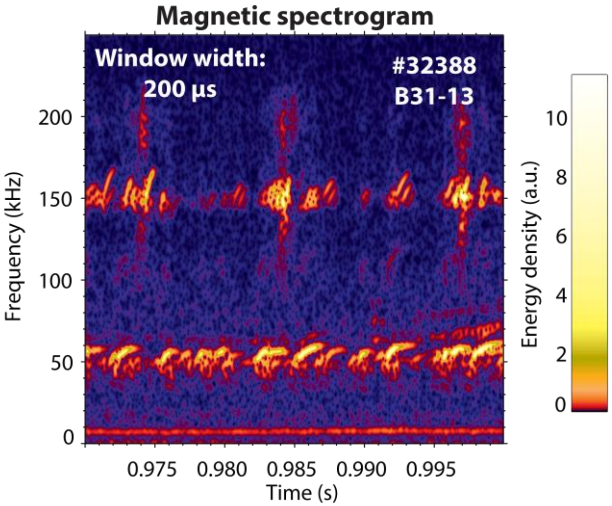
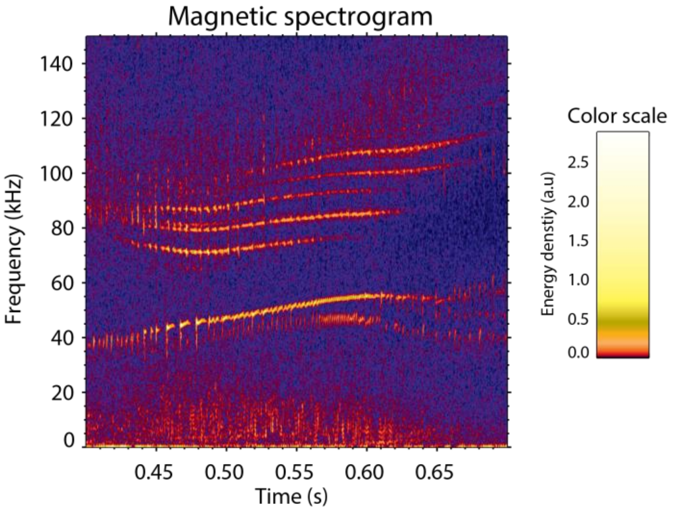
Introduction

- **Super-thermal energetic particles** (EP) can excite instabilities which can lead to an **enhanced transport of fast particles**
- **Nonlinear system**: kinetic and MHD non-linearities are both important
  [Heidbrink PoP 2008]
- **Amplitude correlation can be** caused by both fast ion **phase space coupling** and **direct wave-wave coupling**
- **Our aim**: **investigate** the **signs** of nonlinear **coupling of different fast ion induced modes (TAEs & EGAMs)**
- Support numerical simulations, and compare them to experimental results





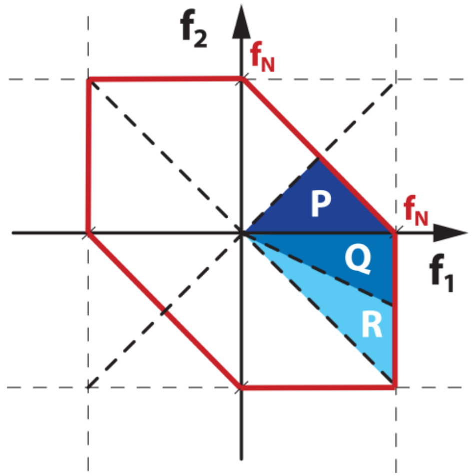
Investigation of three wave coupling

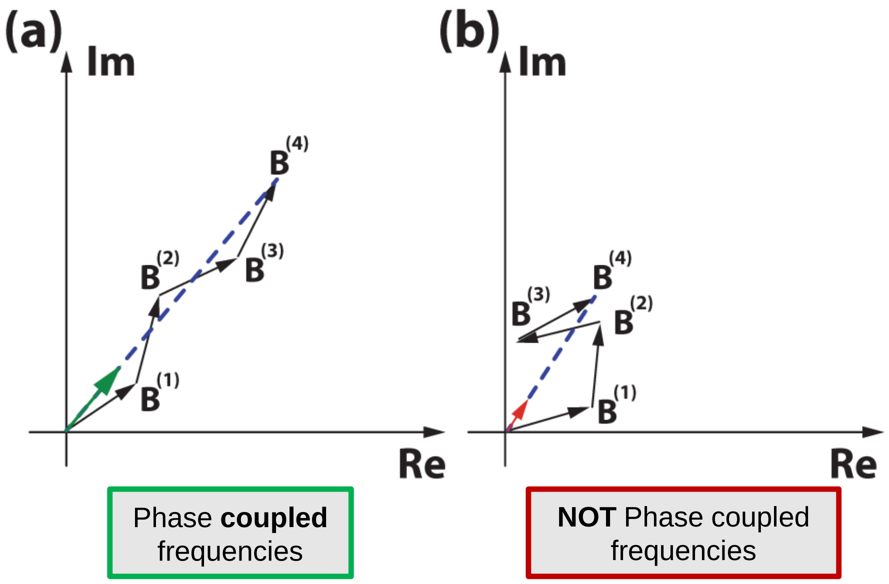
- **Coupling condition:**
- Detection of coupling through phase locking
- Bispectrum calculation as **averaging on the complex** plane
- Real signals yield symmetries

$$f_1 + f_2 - f_3 = 0$$

$$\varphi_1 + \varphi_2 - \varphi_3 = \text{const}$$

$$B(f_1, f_2) = \mathbb{E}\left[X(f_1)X(f_2)X^*(f_1 + f_2)\right]$$





Investigation of three wave coupling

- **Coupling condition:**
- Detection of coupling through phase locking
- Bispectrum calculation as **averaging on the complex** plane
- Normalised bispectrum will give **bicoherence**
- Bicoherence is **bounded [0,1]** like (linear) coherence

$$f_1 + f_2 - f_3 = 0$$

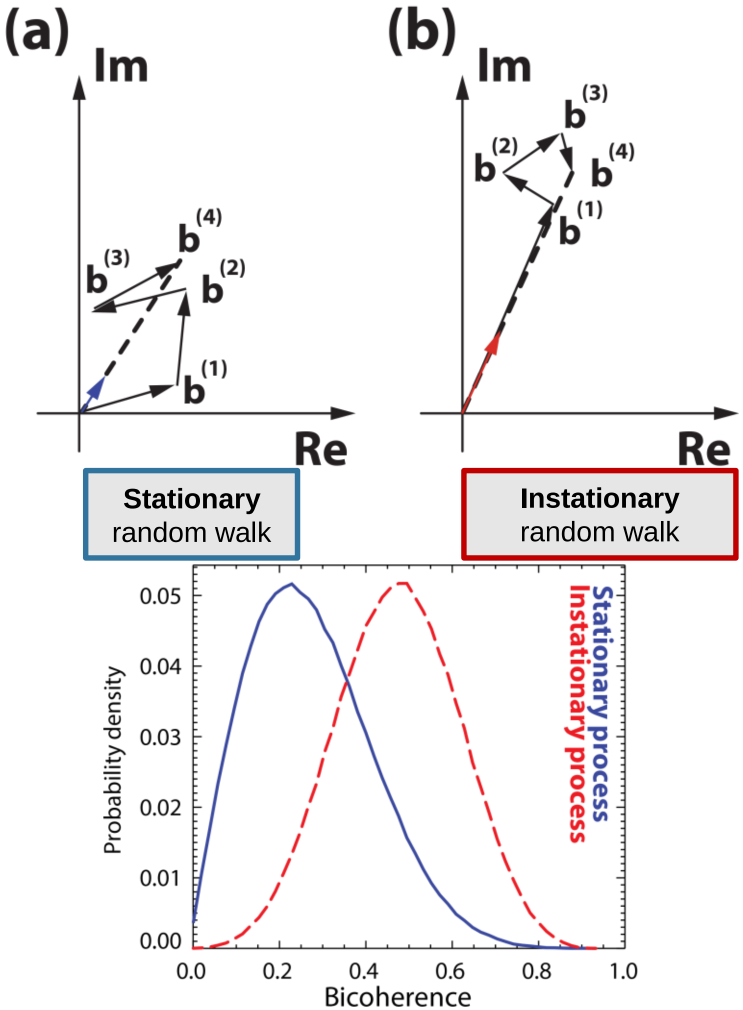
$$\varphi_1 + \varphi_2 - \varphi_3 = \mathrm{const}$$

$$B(f_1, f_2) = \mathbb{E}\left[X(f_1)X(f_2)X^*(f_1 + f_2)\right]$$

$$b(f_1, f_2) = \frac{|B(f_1, f_2)|}{\mathbb{E}\left[|X(f_1)X(f_2)|^2\right]^{1/2} \mathbb{E}\left[|X(f_1 + f_2)|^2\right]^{1/2}}$$

Problem of non-stationarity

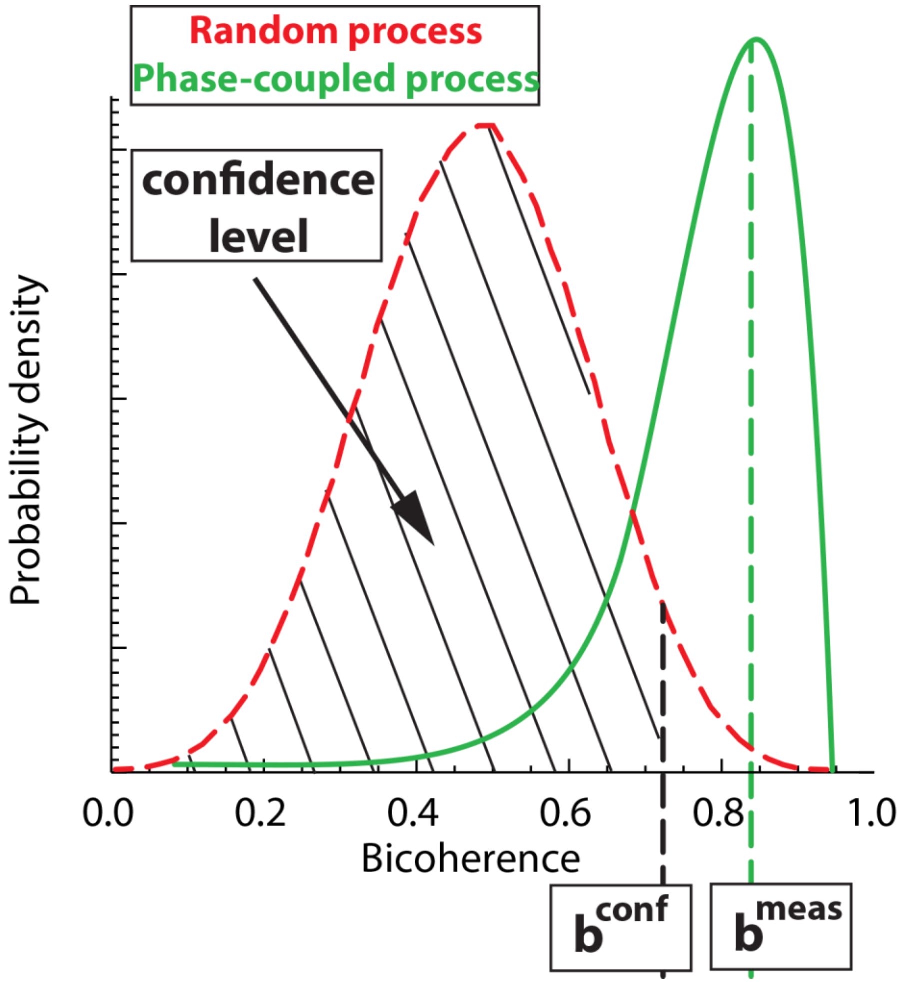
- Main question: What happens if the **method** abovementioned is **applied to non-stationary processes**?
- Random-walk with the **same number of averages** (with **difference in amplitude distribution**)
- Deviations in the probability density functions
- **False high bicoherence: without phase-coupling**



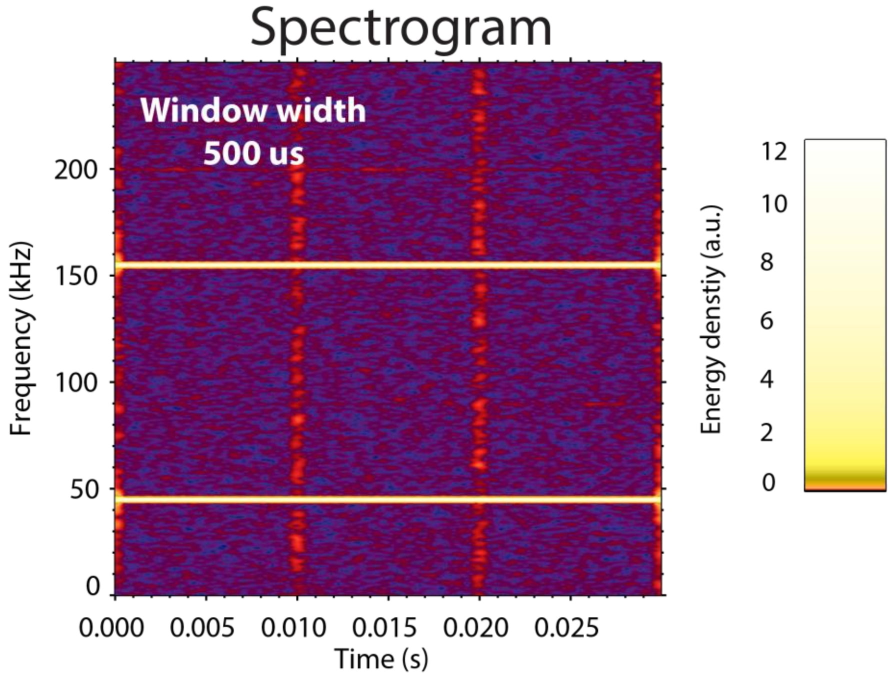
Confidence estimation of bicoherence

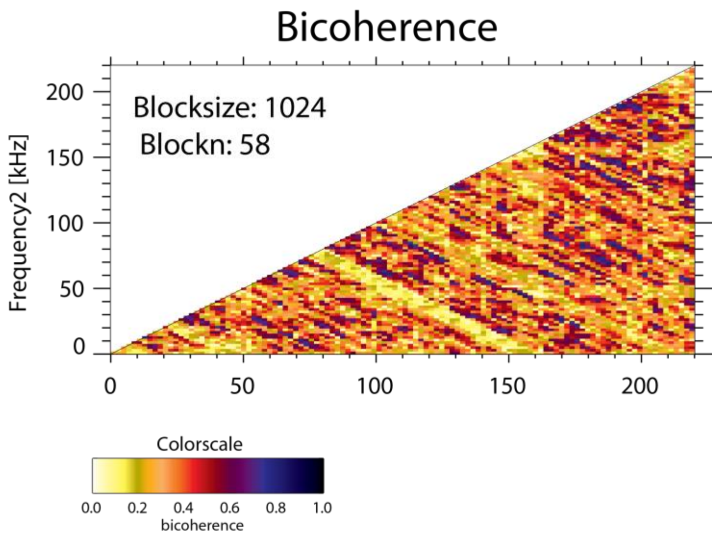
- **Phase-randomized bicoherence density function** generated with **given** (instationary) **amplitude distribution**
- **Level of confidence** can be used as a **filtering parameter**

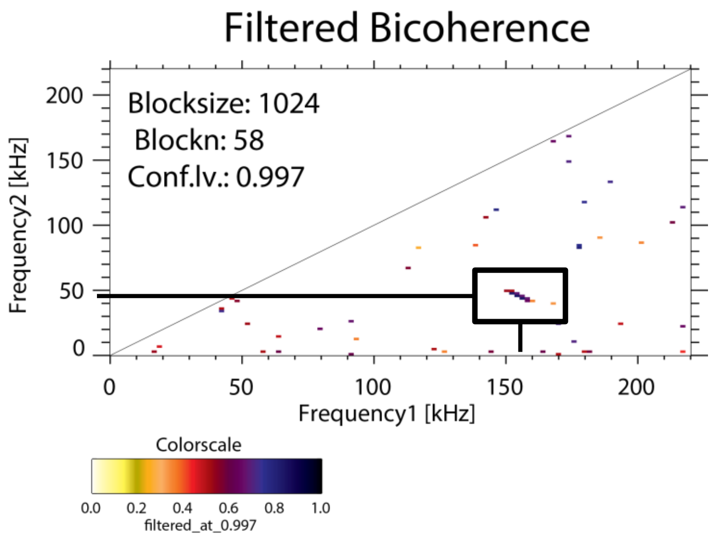
$$\alpha = \int_0^{b^m} \rho(b)\,db$$



Testing method on numerical systems



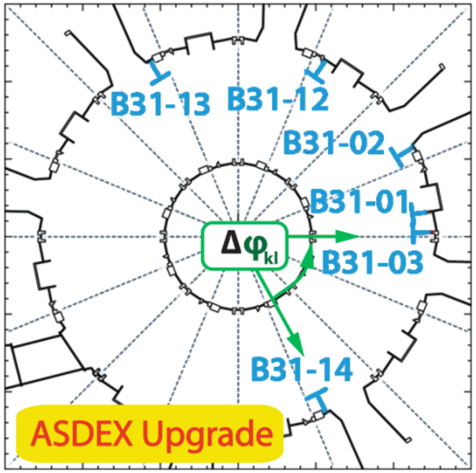


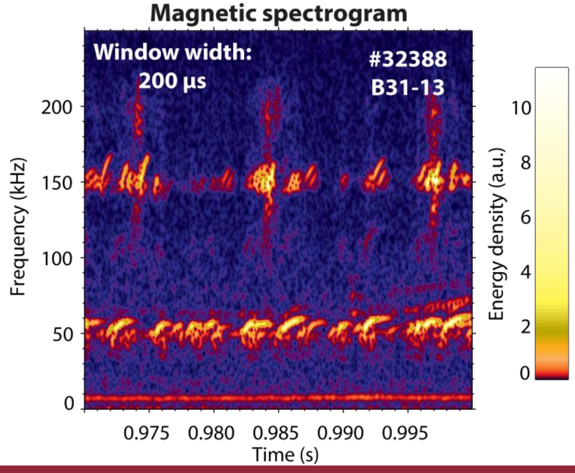


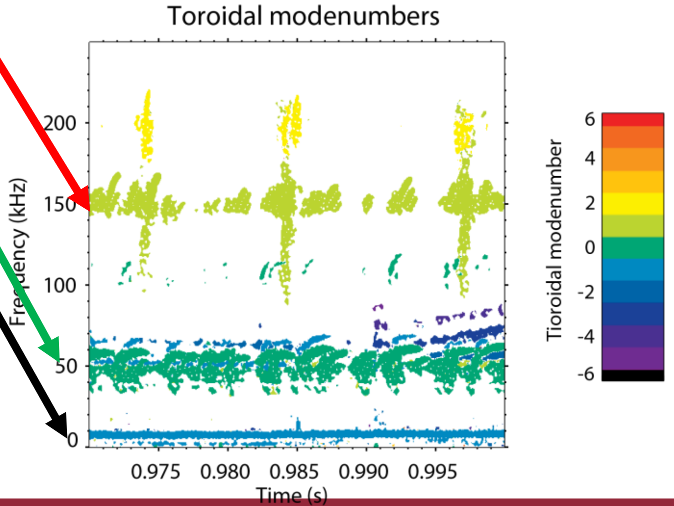
- **Phase-coupled modes** (45,155) kHz with **broadband perturbations**
- **False high bicoherences** in not phase coupled (f_1,f_2) points
- **Filtering can help**

Investigation of experimental results

- **AUG experiments**
- Ballooning probes (mag. diag.) (2 MHz sampling freq.)
- NTI Wavelet Tools
- 3 main frequency regimes:
  - **@150 kHz TAEs (m=-3,n=1)**
  - **@50 kHz chirping EGAMs (-2,0)**
  - @10 kHz low frequency (3,-1) (ion-diagmagnetic direction)

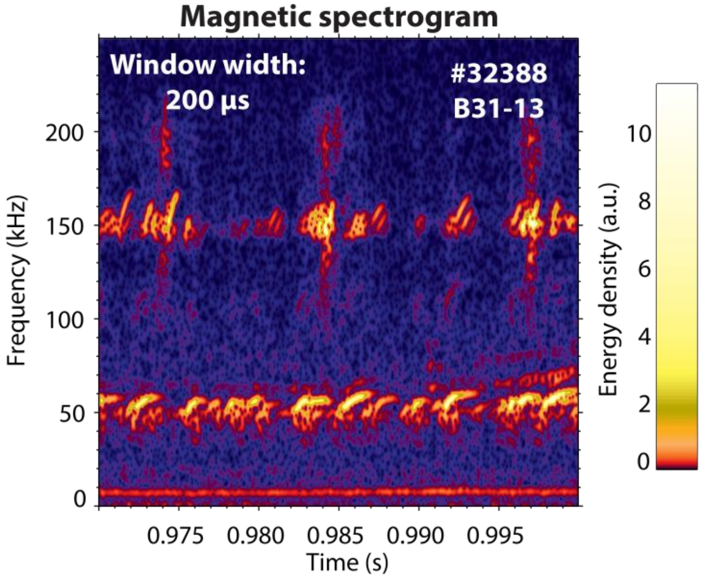


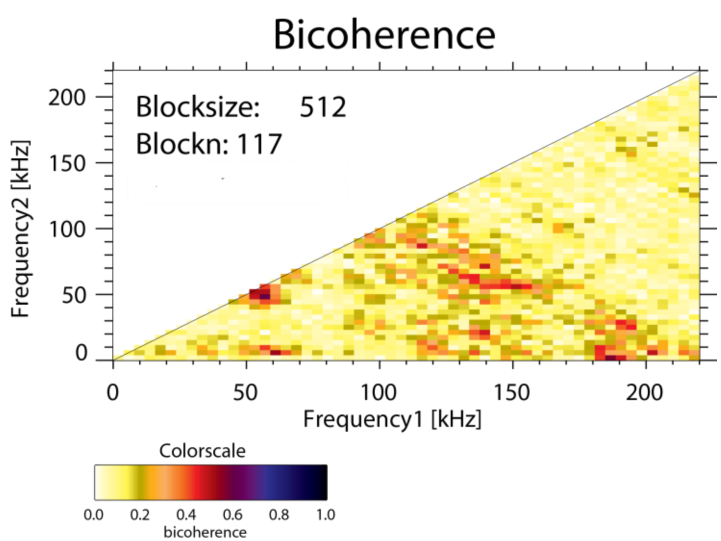


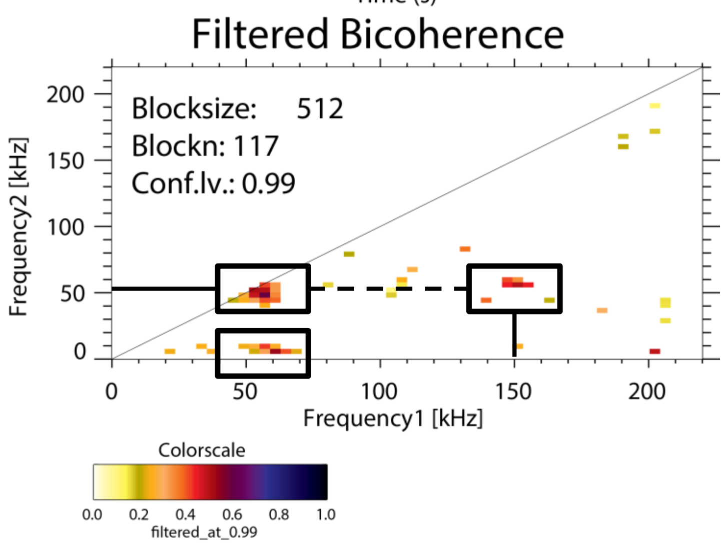


Investigation of experimental results

- **AUG experiments**
- **#32388** strong EGAMs and bursting TAEs
- **Significant phase-coupling** between **EGAM**s and **TAE**s
- Phase-coupling between low frequency mode and EGAM

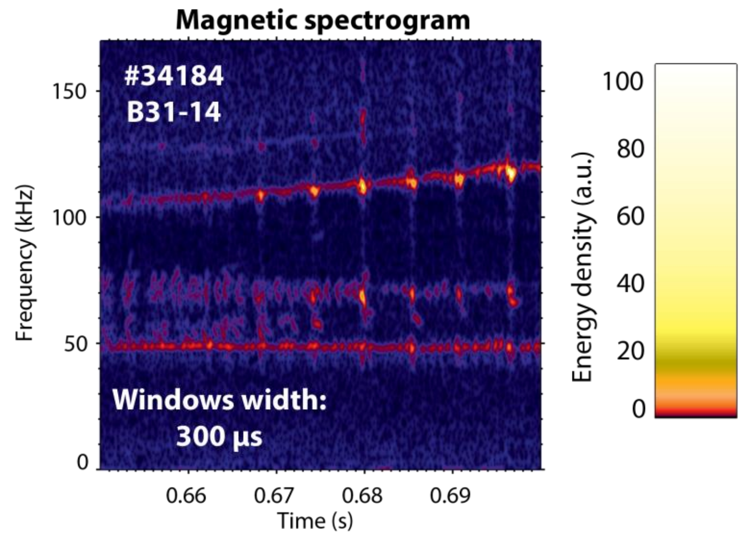


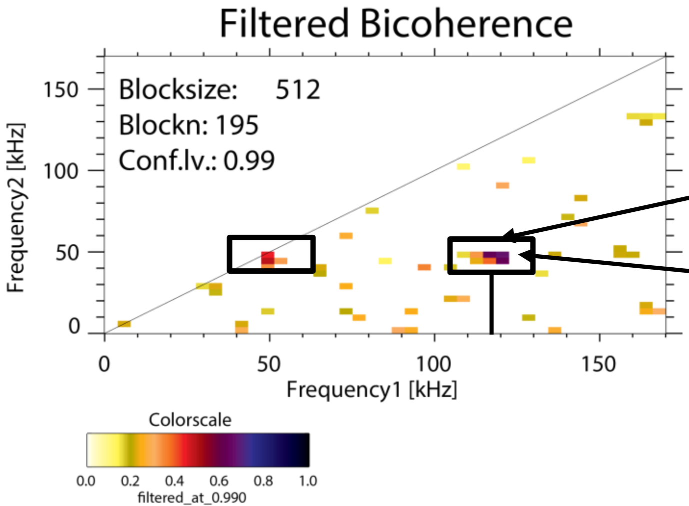


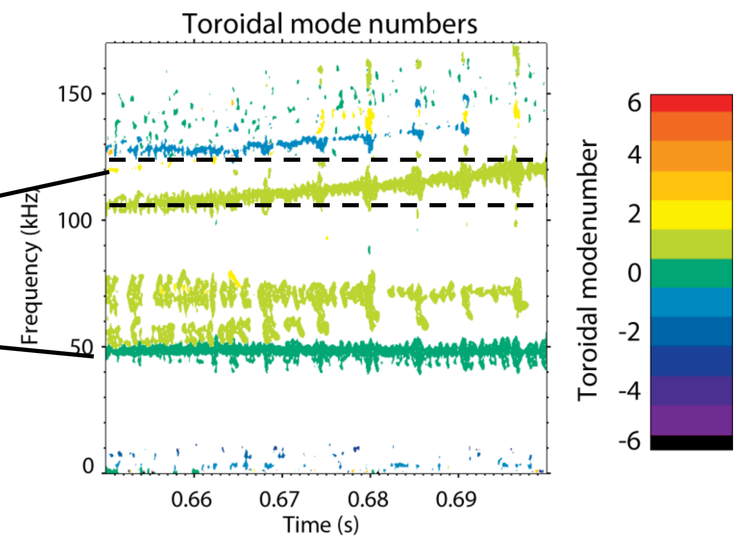


Investigation of experimental results

- **AUG experiments**
- **#34184**
- EGAMs @50kHz
- **n=±1 both co- and counter propagating TAEs** present at the same time @100-130kHz
- **Clear, significant phase-coupling** between **50 kHz** and **110-120 kHz**

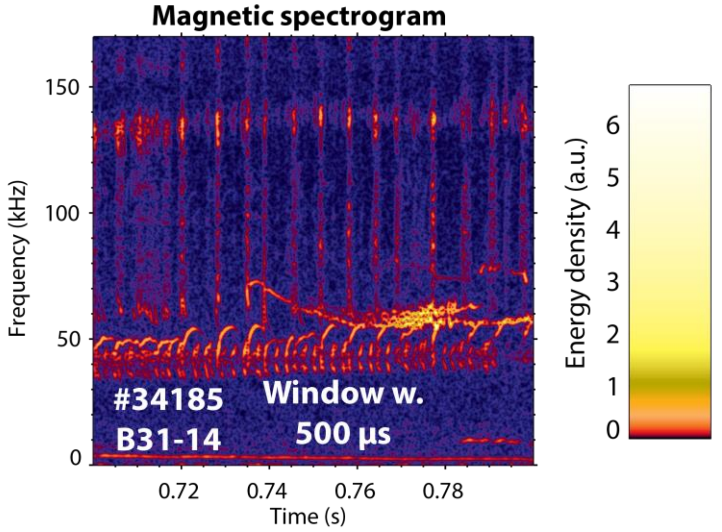


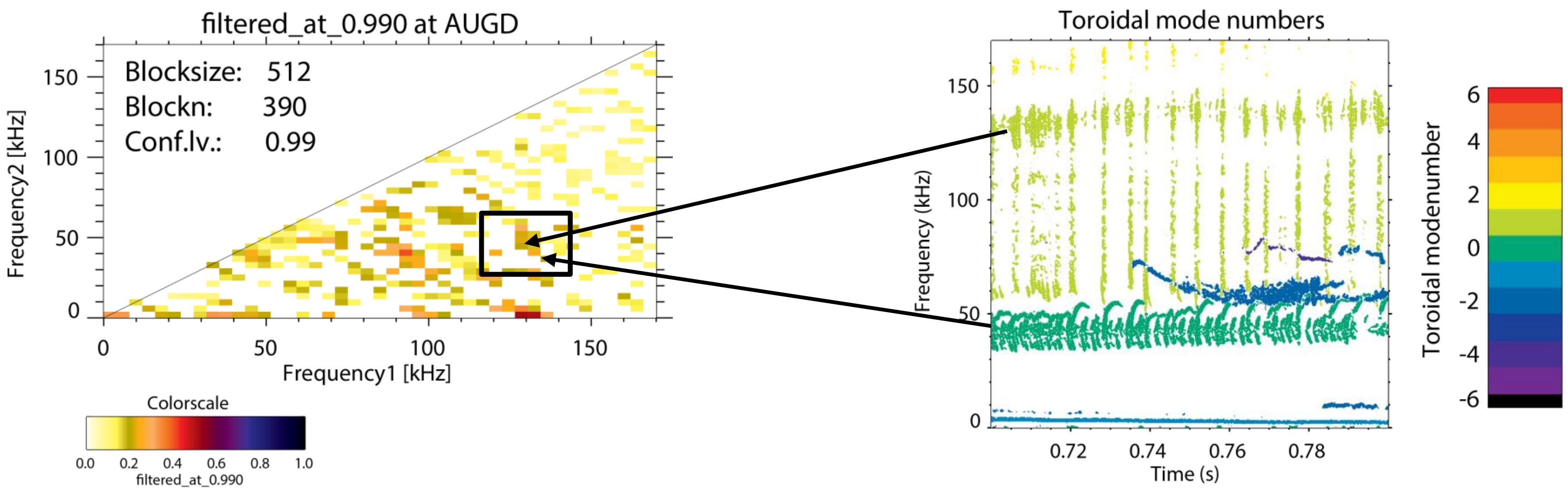




Investigation of experimental results

- **AUG experiments**
- **#34185**
- Chriping EGAMs @50 kHz
- Bursting TAEs @130 kHz
- Week phase-coupling detected, can it be caused by EP-phase space coupling?





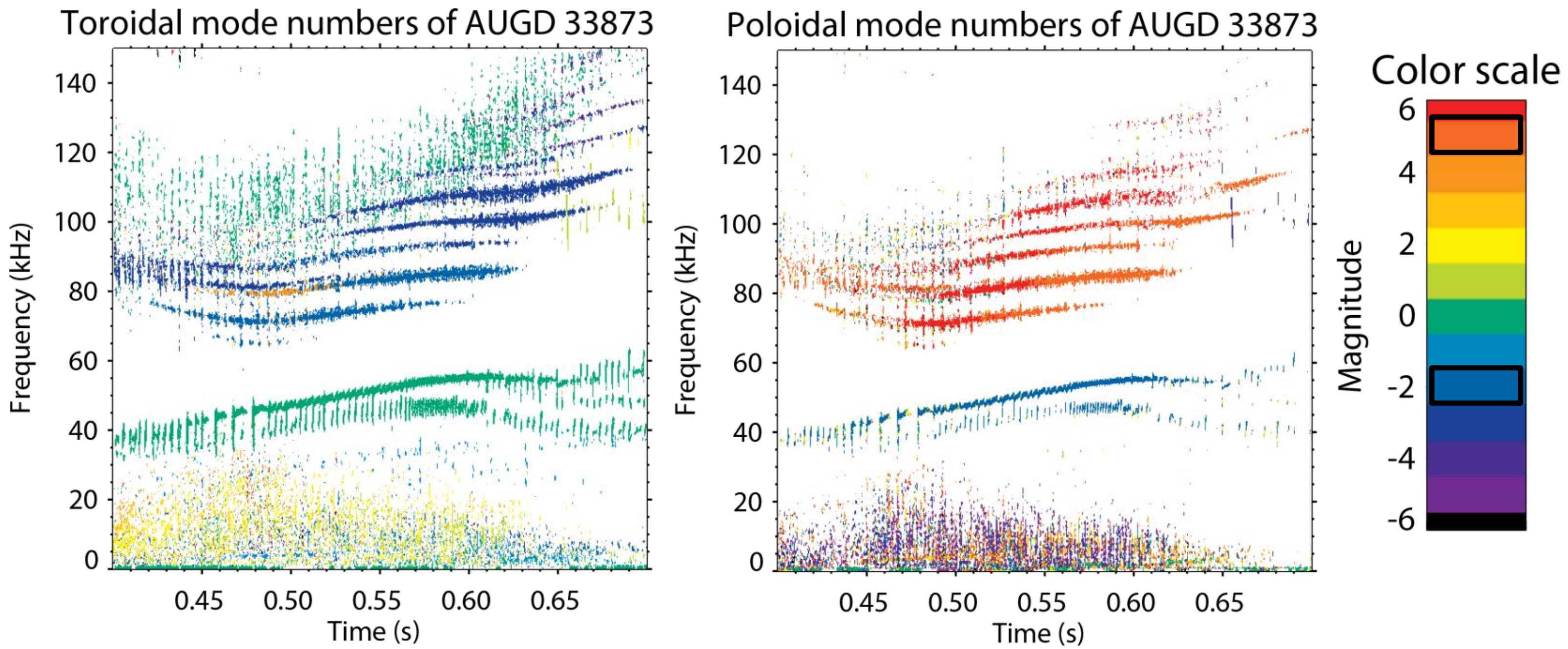
Summary

- EUROfusion ENR-2017 framework:
  - **Experimental** data **analysis** to **support theoretical calculations**
  - Characterization of linear behavior (tools ready, writing up)
  - Investigate the signs of nonlinear interaction of EP driven plasma waves
- Method of **bicoherence** has **been generalized to non-stationary processes**
  - **Tested on model systems**
  - Method **applied to experimental results**, (8 dedicated discharges) where **significant wave-wave coupling** was found between **EGAMs** and **TAEs** (further analysis in progress).
  - Analysis of HMGC provided cases in progress
- Outlook/future plans:
  - **Coupling coefficient estimation**
  - Application of **energy- or/and coherence filtering**
  - **STFT** (wavelet) **bicoherence**

Back-up

More experiments

- **#33873**
- **TAEs** with **identical toroidal modenumber** (n=-2@80 kHz, n=-3@100 kHz) (m=~5-6) (propagating ion-diamagnetic direction)



- #33872, 33874, 33875 no EGAMs and TAEs at the same time

More experiments

- **#34186**
- **Amplitude correlation between EGAMs and TAEs**
- **And wave-wave coupling? >no high bicoherence with filtering**